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WADC TECHNICAL REPORT 53-180
PART V
ASTIA DOCUMENT No. AD 130940

STUDY OF MINIATURE ENGINE-GENERATOR SETS

PART V. SUMMARY REPORT: FEASIBILITY

MARION L. SMITH
OWEN E. BUXTON, JR.
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THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

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WRIGHT AIR DEVELOPMENT CENTER

NOTICES

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EQUIPMENT LABORATORY
CONTRACT No. AF 18(600)-192
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared in the Mechanical Engineering Department of The Ohio State University under Contract No. AF 18(600)-192, "Study of Miniature Engine-Generator Sets" with The Ohio State University Research Foundation. Work was conducted under Project No. 6058, "Electrical Generation Equipment," Task No. 60266, "Development of Miniature Engine-Generator Sets," (formerly RDO No. 656-2112), and was directed by the Equipment Laboratory, with Dr. Edwin Naumann and Lt. R. G. Leiby serving as project engineers.

This report summarizes the work of the entire project, conducted from June 1952 through September 1956. Other Technical Reports and Technical Notes issued during the period of the contract, and referred to in this final report, are WADC TR 53-180 (May, 1953), WADC TR 53-180 Part II (December, 1954), WADC TR 53-180 Part III (March, 1956), and WADC TR 53-180 Part IV (October, 1956).

ABSTRACT

Information is presented concerning the feasibility of miniature engine-generator sets as power sources for 35 to 400 watts capacity. A summary is given of the present and potential performance characteristics of miniature reciprocating internal combustion engines and miniature a.c. and d.c. generators. Over-all weight, volume, and fuel consumption data are presented, both for specific prototypes in their current state of development, and for potential systems. Reliability, the most serious problem in this size of equipment, is discussed. An outline is included of optimum design features for miniature engines and generators for this type of application.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

J. E. Rowland

J. E. ROWLAND
Chief, Systems & Power
Conversion Section
Electrical Branch
Equipment Laboratory

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INTRODUCTION

With the tremendous progress that has taken place in recent years in the development of electrical and electronic equipment, many new applications for the use of such equipment for military purposes become evident, both for airborne and for ground installations. Many of these applications involve the use of electrical devices for communication, detection, guidance, control, heating, etc. Sometimes it is desirable to provide with this equipment an integral power source isolated from any other electrical or mechanical system.

As in all equipment which may be airborne in some stage of its application, the power source should be of minimum weight and volume for the power developed. Likewise, a high degree of reliability is essential, as it is for any type of military equipment. Several types of power sources might be developed for these applications, including various types of primary and secondary batteries, some ingenious turbine-driven generator sets, and reciprocating internal combustion engine-generator sets.

It was the purpose of this project to study the feasibility of miniature engine-generator sets, in which a reciprocating internal combustion engine was used as the prime mover. Net ratings of 35 to 400 watts were established as the size range of interest. It was desired to ascertain the advantages and limitations of this type of equipment, the optimum design parameters, and the components that warranted further development work.

Preliminary estimates of the power per unit weight and volume from miniature engine-generator sets, based on specifications of commercial engines for model airplanes and boats, made such units appear very promising. Numerous types of miniature engine designs were available or seemed possible. At the outset of this project, however, very little technical information was available concerning the relative merits of the various designs or of the potential ratings or degree of reliability which might be attained. In particular, little engineering data were available to permit accurate estimates of the major differences which would exist between design parameters and performance of miniature engines as compared to the larger, well-developed reciprocating engines.

This report is intended to summarize the findings of this investigation of miniature engine-generator sets, which has been under way for the past four years. It deals with the potential capabilities of miniature engines and generators and with the reliability which might be expected from them. Conclusions reached regarding optimum design features of such units are discussed.

Manuscript released by the author 11 September 1956 for publication as a WADC Technical Report.

Four other Technical Reports and Technical Notes have been written pertaining to the work of this project. WADC TR 53-180 (May, 1953) describes the effort during the first year of the evaluation program. It describes the special test apparatus and instrumentation which had to be developed to conduct an experimental program with this miniature equipment. Specifications and performance curves of commercial model engines are included, along with a discussion of some of the typical malfunctions and part failures which were experienced. Some data on miniature d.c. generators are presented. This first report includes an outline of the long-range development program which was followed throughout this evaluation project. Reference is also made to the design features of the first experimental engine, developed by this project for the purpose of investigating optimum design parameters. Early in the project, a short study was made to find an approximate comparison between batteries and potential miniature engine-generator sets on a weight and volume basis. This comparison and the assumptions made to arrive at it are also presented in the first Technical Report.

WADC TR 53-180 Part II (December, 1954) presents the results of the experimental program conducted from May 1953 through December 1954. It deals with the performance characteristics of miniature engines, and the fuel and lubricant requirements peculiar to them. Most of the experimental data presented in this second report were obtained from special miniature engines designed, built and developed by the personnel of this project specifically as test vehicles for this study. A discussion of some optimum design features and limitations of these engines due to reliability is included.

The third report of this project, WADC TR 53-180 Part III (March, 1956), presents design and performance information concerning miniature d.c. generators. These data were obtained experimentally by this project, and include results for some miniature commercial generators as well as for some special types designed and built for experimental purposes. A design procedure is included to aid in the design of new miniature d.c. generators for specific applications.

The details of the experience obtained during evaluation of various component systems of an over-all engine-generator set are reported in WADC TR 53-180 Part IV (October, 1956). This work covers the last one and one-half years of the project. It presents information on starting characteristics, performance at extremes of environments, engine-generator cooling systems, carburetion systems, engine speed control, and noise reduction.

During the term of the project, some work was conducted on all major phases of the investigation presented in the original specification, DCEEE3-1, 25 May 1951. As time would not allow intensive investigation into all phases of design and performance of engines, generators, and all component systems, an effort was made to concentrate on those areas where initial studies would be most advantageous, but also to conduct exploratory studies into the other phases of the work. The study includes evaluation of related equipment reported in the literature, analysis of results obtained from special test vehicles (Figures 1 and 2) designed and built by this project for this purpose, and compilation of the experiences and results from other laboratories on similar or related equipment.

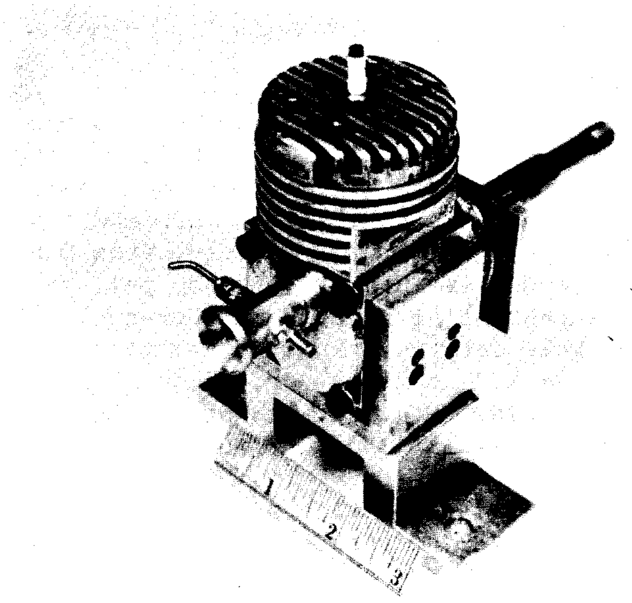


Figure 1. Mark III, Two-Cycle, Cross-Scavange, 0.89 Inch Bore, 0.66 Inch Stroke, 0.45 BHP at 13,000 rpm

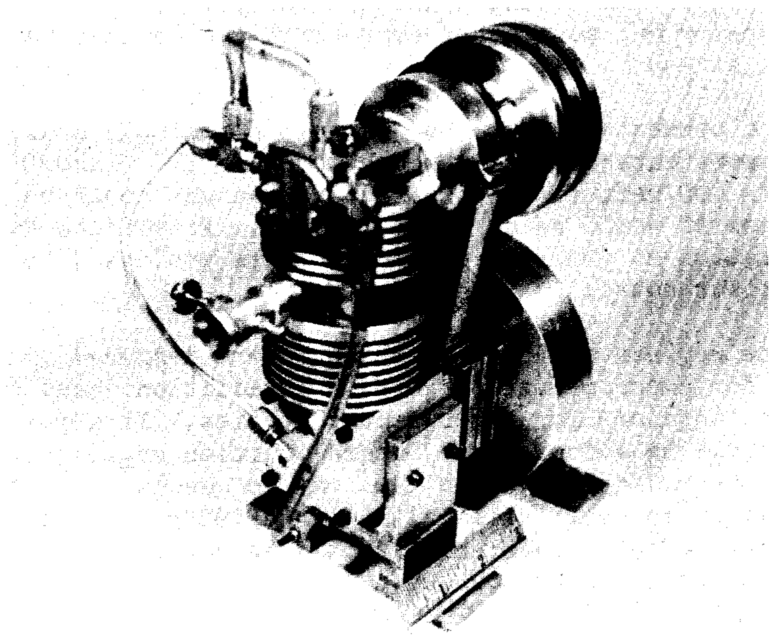


Figure 2. Mark IV, Four-Cycle, Valve in Head 1.015 Inch Bore, 0.827 Inch Stroke, 0.535 BHP at 9,000 rpm

SECTION 1

SUMMARY

In search for a compact, lightweight power source for 35 to 400 watts capacity, the potentialities of miniature reciprocating engines as prime movers to drive small, high-speed generators have appeared attractive. These engines will operate at speeds of 12,000 rpm and higher. In sizes of 0.4 to 2 cu in. displacement, they develop from 0.6 to 2 bhp per cu in. of displacement, with BMEP values of 40 to 80 psi. Fuel consumption as low as 0.8 lb per bhp-hr is attainable in four-cycle engines, or 1.5 lb per bhp-hr in two-cycle designs. Fuel consumption for the engine-generator set could be as low as 1.5 lb per kw-hr, although somewhat higher fuel consumption rates are likely. Starting at some rather wide extremes of temperatures and operating at altitudes up to 22,000 ft. or more is possible.

The most serious limitation with such power sources is the problem of achieving reliability with the very compact, lightweight equipment which would be desirable for airborne applications. Reciprocating engines of the model aircraft engine size and weight can not be made reliable enough for use in military engine-generator sets. The most likely prospect along these lines which seems possible for the next several years would be a compromise between the size and weight of engines and components used for model aircraft size and those now available as commercial small engines. The carburetion system and the ignition system are the most serious limitations to achieving reliability. They fail to function properly when scaled down in proportion to the reduction in cylinder size and net power required. The generator and most other components can be made to work satisfactorily in small sizes.

As a consequence, it appears that a reliable small engine-generator set of 200 watts capacity would weigh about 16 lb, without fuel, or 0.08 lb per watt. In 400 watt sizes this specific weight could be reduced, but in 50 watt sizes it would be at least doubled. Provisions for automatic starting and operation at extremes of environments would add to the size and weight of the power source.

Nine engines and four generators were designed and built for this project for experimental purposes. In addition, many other items of equipment were obtained for experimental studies. It appears that the prime mover should be a four-cycle, spark-ignition engine, of either overhead valve or L-head design. The fuel may be gasoline or, for short periods of operation in small size units, liquefied petroleum gas. With adequate development effort, such units should be capable of providing satisfactory service as small power sources.

SECTION 2

POTENTIALITIES OF MINIATURE ENGINE-GENERATOR SETS

2.1 GENERAL

Any term such as miniature must be used in a relative sense. For the purpose of this report, the term miniature engine-generator set is intended to denote a system which would give a net power output of 35 to 400 watts, with specific weights, measured in lb per watt, much lower than present commercially available equipment. This arbitrary choice of size is selected on the basis of the range of capacities to be studied by this contract, as designated by the initial proposal. From this definition for the engine-generator set, the size range of engines which might be called miniature are defined arbitrarily as the size necessary to drive, at sea level, a 35 to 400 watt generator plus all desired accessories (cooling fan, ignition system, governor, etc.,) using only 60 per cent of its maximum rated sea-level power. This latter provision would permit the engine to be operated at its maximum permissible altitude and still maintain rated capacity. At the same time it would allow some reserve for overload, or operation at reduced mean effective pressures, to increase engine life. By this definition, at usual values of generator efficiency and with common engine accessories, the rated outputs of engines termed miniature would be 0.2 to 2.2 bhp. If an engine is to be called miniature, it must have a reasonably high power output per unit volume of piston displacement. For engines of this size, specific power outputs of 0.7 to 2 bhp per cubic inch of displacement can be achieved. Assuming a conservative value of 1 bhp per cubic inch results in a cylinder displacement of 0.2 to 2.2 cubic inches. Referring to Figure 3 which shows specific weights of various types of engines, it is arbitrarily defined that a miniature engine should weigh not more than three lb per bhp. Engines of low power ratings which weigh more than this could be termed small but not miniature.

The work of this project has been made difficult, and the results are therefore more restrictive than might be expected, because very few engine-generator sets in this size range have been built to date. Only a few prototype models have been constructed, and no units are available commercially. Since the purpose of this contract was to explore the feasibility and desirable design features of these miniature power sources, and not to develop a given piece of hardware to meet a particular application, no complete engine-generator sets were constructed by this project. Instead the weights and volumes of all known and available prototype models developed by others were analyzed, and the results extrapolated to give some indication of the optimum weight and size of system which might be developed. The operating and design experience gained by this project was used to influence the extrapolation of the optimum weight of system which conceivably could be developed. Accurate estimates of total weight and size for units which might be required to operate at very extreme environmental conditions

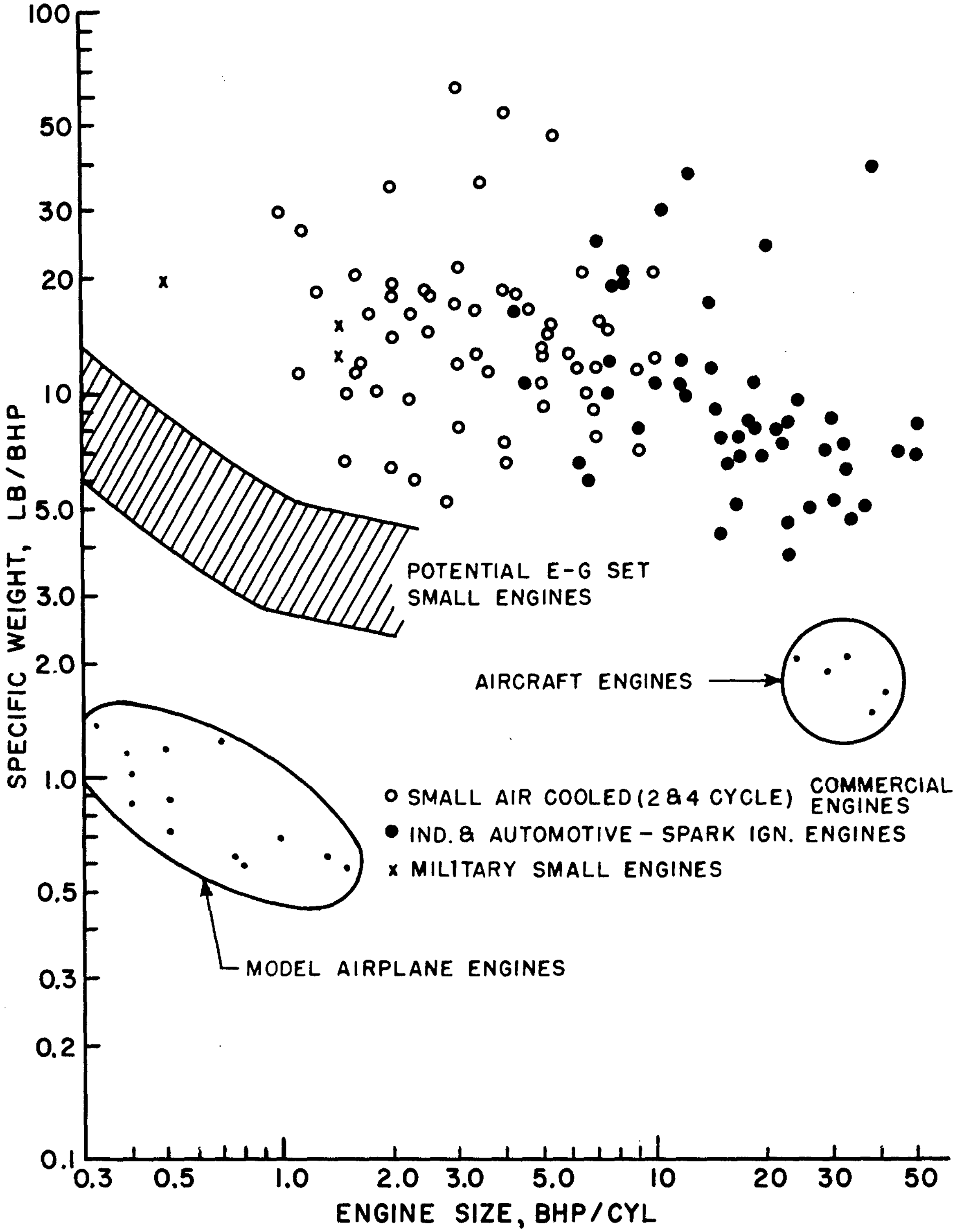


Figure 3. Specific Weights for Various Engines

are almost impossible to make. No miniature engine-generator set known at the present time can operate at an altitude greater than about 22,000 feet. To build a unit capable of operation at higher altitudes would necessitate a large blower for supercharging the engine, which would require a much greater power output from the engine. The power requirement would increase so rapidly to drive a small, and necessarily inefficient, supercharger, that the engine would very quickly exceed the size which could be called miniature, by any stretch of the definition. The same problem would be encountered for units which must start automatically and operate for a long period of time unattended. The complications of engine design are such that any requirement of this type would necessitate a considerable increase in size, weight, and complexity of the system, if any reasonable degree of reliability is expected.

Therefore, estimates of size and weight are based on engines which would operate at low altitudes where engine supercharging is not required. Most data do not include provision for automatic starting.

Miniature engines of this size have been available commercially for use in model airplanes, racers, and boats. These can be purchased in a wide variety of designs. They operate at speeds of 6,000 to 18,000 rpm. Models which develop power outputs from about 0.1 hp or less up to 2 or 3 hp can be purchased at very reasonable prices. It was found when exploring these types of engines, that they did a remarkably good job of producing high power for low engine weight, as illustrated in Figure 3. Reliability is discussed more fully in Section 3, but summarizing, the ease of starting and over-all reliability of these engines was not adequate for military purposes. These engines were not made to withstand continued operation at rated power, as would be the case for engine-generator applications. In many cases, mechanical failure occurred within a few hours, or even minutes, of operation at high load. Therefore, while very low specific weight, in lb per hp developed, can be obtained with these types of engines, they are not durable enough for engine-generator purposes and the specific weight figures are not realistic.

Larger engines for driving lawn mowers, bicycles, chain saws, etc., are also available commercially. By the definition of miniature set for the above, these engines would have to be classified as small, but not miniature. As shown in Figure 3, the specific weight of these engines is about the same as those of automotive and industrial engines. These engines all operate at 1800 to 4000 rpm. Hence they require a much larger displacement for the same power output than the model engines.

What is desired in the way of a prime mover for a miniature engine-generator set must be a compromise between the model engine design and the designs of small engines. As a result, the data for specific weight and size per hp for either of these classes of engines do not permit realistic estimates of system weights for military miniature engine-generator sets.

2.2 ESTIMATED SIZE AND WEIGHT

Because so few complete engine-generators sets of the miniature or even small size have been built, it is difficult to arrive at accurate values of specific weight per unit of power rating, or of over-all size. To further complicate the problem, those few units which have been built have been designed for widely different types of applications. Hence, completely different criteria have guided the direction in which the design would go; minimum weight and size have in some examples been of minor importance. The degree of reliability, ability to operate in extremes of environment, and ability to start and operate unattended all are dominant factors in determining the over-all system weight and size.

To give some indication of the size and weight of engine-generator system which might be attainable, a breakdown of the size and weight of various engine and generator components are presented in Table I. The first two columns of data present actual weights and sizes of the components of the power supply which was developed by the Ruckstell-Hayward Company for Radio Beacon AN/ART-27 (XA-1). (See reference 13). This is considered to be a good example of the weights and sizes which are attainable in miniature equipment, since this power source was well designed, with a definite view to achieving minimum weight and size. Although this power source never met its performance specifications, it is believed that the failure to do so was an indication that the initial specifications were probably unattainable by this means, since the engine-generator system itself was well designed and developed. The automatic starting system and the fuel system were the key sources of trouble with this unit.

The third column in Table I lists the estimated minimum weight which might be expected for components of this type without sacrificing seriously on the reliability. In fact, it is the opinion of the authors, after considerable experience on this project, that good reliability will not be achieved in an engine as light as that shown in the "estimated minimum weight" column, certainly not without a long, expensive development program. A more detailed discussion of the effects of weight and size reduction on reliability is made in Section 3.

As with any power generating equipment, the rating is a somewhat arbitrary value and depends upon many factors other than the actual maximum rate of energy release for a given set of conditions. Table II shows how the specific weight and size of some of these engine-generator sets vary, depending upon the rating assigned as well as upon the actual weight and size of the equipment itself. For example, Item 2 shows that the Ruckstell-Hayward Beacon unit could be rated as high as 250 watts for shorter periods of operating time; thus, the specific weight for this rating becomes 0.05 lb per watt, without fuel. The specific size changes from 4.5 cu in. per watt at standard rating to 1.8 cu in. per watt at the short term rating.

Item 3 lists the "estimated minimum weight" system shown previously in Table I. With a reasonable high rating of 200 watts, which is possible with this system at low altitudes, the specific weight is 0.03 lb per watt. The

TABLE I. TYPICAL WEIGHTS AND SIZES OF A 100 WATT ENGINE-GENERATOR SET AND COMPONENTS*

Component	Weight, lb*	Volume, cu in*	Estimated minimum weight attainable, lb
Engine, bare	1.55	21.00	1.40
Engine Mounting Flange	0.13	1.25	0.13
Temperature Regulating Assembly, for adjusting flow of cooling air	0.16	1.00	0.00
Exhaust pipe (no muffler)	0.08	0.98	0.04
Carburetor	0.07	1.22	0.04
Carburetor altitude control	0.05	0.69	0.00
Choke coil	0.24	1.50	0.24
Engine Assembly, Total	2.28	27.64	1.85
Generator Rotor	0.80	3.66	0.80
Generator Housing Assembly, including Cooling Fan Scroll	1.43	24.69	1.43
Cooling Fan Rotor	0.15	2.45	0.15
Generator Assembly, Total	2.38	24.69	2.35
Cover Assembly, Total	0.48	---	0.00
Fuel System Assembly, Total, without fuel (Includes fuel tank for 24 hours of fuel supply, fuel filters, pressure regulators, and nitrogen storage tubes for automatic starting)	4.48	287.00	1.30
Hydrogen cylinder and injector	0.62	4.80	
Vane starting motor and clutch	0.94	8.85	
Nitrogen regulator Assembly	0.27	2.11	
Starting System Assembly, Total	1.83	15.76	0.50
Engine-Generator Set, Totals	11.45	448	6.00

*Actual Data as measured from prototype of Ruckstell-Hayward Power Supply for Radio Beacon AN/ART-27 (XA-1)

TABLE II. WEIGHT AND SIZE OF SOME PROTOTYPE MINIATURE ENGINE-GENERATOR SETS

Item No.	Engine-Generator Set	Rating, watts	Weight, lb w/o fuel	Over-all volume, cu in.	Specific weight, lb/watt w/o fuel	Specific size cu in/watt
1	Ruckstell-Hayward Beacon, Rated	100	11.45	448	0.11	4.5
2	Ruckstell-Hayward Beacon, for short term	250	11.44	448	0.05	1.8
3	Estimated Minimum Weight System	200	6.00	448	0.03	2.2
4	Armed Forces Standardized Engine (1-1/2 hp)	600	35.00	3100	0.06	5.2
5	Armed Forces Standardized Engine (1-1/2 hp)	200				

specific size is 2.2 cu in. per watt. The specific size values listed for the first three items includes a fuel tank volume sufficient to supply the engine for approximately 24 hours. It should be noted in Table I that the components for the "estimated minimum weight" system include only a 0.5 lb starting system, which probably could be achieved only by hand starting. No provision was made for a cover plate to give a totally enclosed engine-generator package, which may be required in certain applications. Another factor of importance in estimating a minimum specific weight of system is the rating required. This same item of equipment might well be rated 100 watts for some applications, which would immediately double its specific weight and size. Also, it would be impossible to reduce the weight and size of the engine, generator and other components proportionately for ratings of 100 to 35 watts. It is the opinion of the authors that a reliable system for 35 watts capacity would weight at least 4 lb, as a minimum weight system. Thus, the specific weight would be 0.11 lb per watt, as contrasted with that for the 200-watt rating. It is possible that a good unit of 400-watts capacity might be developed with an over-all equipment weight of about 10 lb, giving a specific weight of 0.025 lb per watt. In fact, this system could be developed from present knowledge and experience much more readily and probably with a more satisfactory end product, than the 200 watt system weighing 6 lb. It does not appear likely that either of these units at these weights would have an adequate starting system for automatic, unattended operation, or reserve engine power to produce rated capacity at the maximum operating altitude.

In Section 3, it is concluded that satisfactory reliability can be achieved only by providing for larger, more rugged parts than are used in the miniature engines investigated. Crankshafts, valves, crankcases, etc., must be designed to prevent excessive distortions and to withstand unusually high stresses caused by vibrations and irregular loadings. Thus, a more realistic specific weight for systems of 100 to 200 watt rating would be 0.1 to 0.15 lb per watt. With an adequate starting system, or with provision for operation at extremes of environments, specific weights may be approximately 0.2 lb per watt. With smaller power sources for ratings of 35 to 50 watts, to achieve good reliability under adverse conditions, it is possible that specific weights of 0.5 lb per watt may be required.

Figure 3 shows the compromise in engine design which should be made to attain reliability with current design techniques. The zone marked "potential E-G set small engines" shows values much higher than those for commercial model airplane engines, to achieve the desired reliability. In fact, the weights exceed the 3 lb per hp figure arbitrarily selected as the weight limit for miniature engines. At the same time, this predicted zone reflects a considerable reduction in engine size, with some reduction in weight per hp, over the practice with current small commercial engines or even the new Armed Services Small Industrial Engines, (Reference 5). Thus, it is felt that this zone represents a realistic estimate of small engine performance. It is an attainable goal, but one which has not yet been reached by any prototype engine with good reliability. It shows that the feature of reliability requires that the engine be "small" and not "miniature," even though the power source rating may be only 35 to 400 watts.

In summary, specific weights of miniature engine-generator sets of 0.03 lb per watt are potentially attainable, but are optimistic at the present. A reasonably reliable, hand-starting, power source for 200 watts capacity in a moderate environment could have a specific weight of 0.08 to 0.1 lb per watt. For the same system rating, with automatic starting and provision for operation at some extremes of environmental conditions, a specific weight of 0.15 to 0.2 would probably be required.

2.3 COMPARISON OF SIZE AND WEIGHT WITH BATTERIES

As discussed in the preceding section, a generalization as to the over-all weight and size of a miniature engine-generator set for a given length of operating time is difficult to make, because of the wide variety of specifications which the system may be required to meet. Figure 4 is presented to give a quick estimate of the over-all weights of engine-generator sets and how they would compare with batteries for power sources. The figure shows the total weight of power system plus fuel which would be required for a given length of operating time at a continuous power output. As stated previously, the lightest weight system which can be produced and still maintain a reasonable degree of reliability would probably weight at least 0.03 lb per watt of rated capacity. Such a unit, where minimum equipment weight is a primary objective, likely would have a specific fuel consumption of about 3 lb per kw-hr. Heavier systems, which will probably be needed to achieve the reliability desired and yet be capable of operation at the greater extremes of environments, would weigh 0.1 to 0.2 lb per watt, without fuel. These larger units, with lower specific power outputs, could have a fuel consumption of 1.5 lb fuel per kw-hr. To achieve good reliability at extremes of environments, with automatic starting and unattended operation, it is possible that the system weight could go as high as 0.5 lb per watt for units with very small ratings. The length of operating time required with unattended operation is also a factor in determining the initial weight of equipment, since larger, heavier fuel tanks would be required when extended operating times without refueling are required.

The values of estimated minimum weights of battery systems are based on data from Figure 18, page 37 of WADC TR 53-180 (May, 1953). Appendix I of that report contains a discussion of the minimum lb per watt which can be expected for various types of batteries. In estimating the battery weights per unit of energy released, the performance characteristics of several types of cells were considered. In each instance the battery was assumed to be operating at its most ideal environmental condition. As shown in Figure 18 of the report just mentioned, for operating times up to 10 hours silver peroxide cells showed the lowest weight per unit of energy of any of the cells studied. For periods of continuous discharge up to several days, the zinc cells were considered superior, again on the basis of the weight of battery required for a given power output. Where

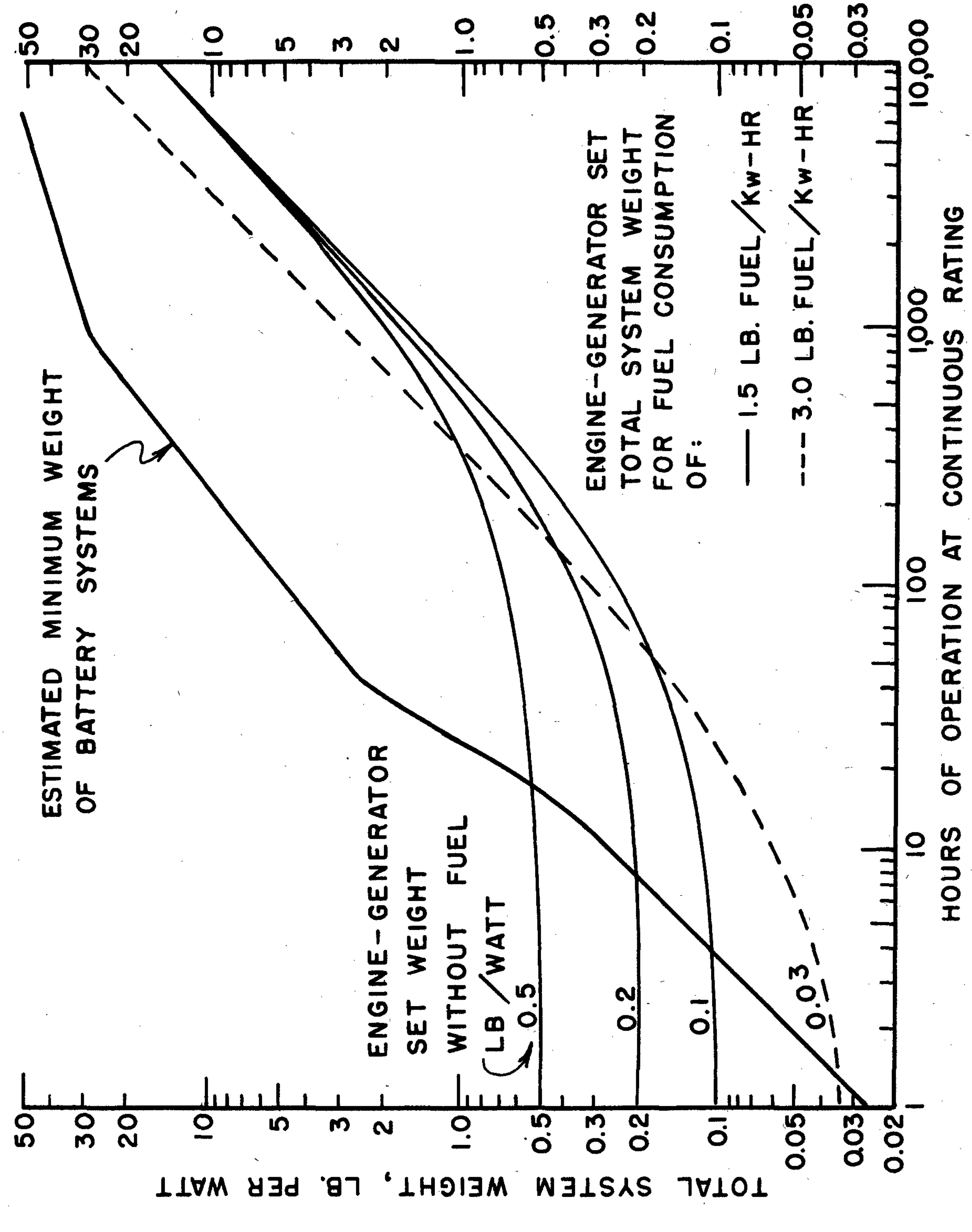


Figure 4. Comparative Weights of Engine-Generator Sets and Batteries

several months of operation without recharging was involved, the air-depolarized cell showed a weight advantage. Magnesium - silver chloride batteries and lead-acid cells were also considered in the weight evaluations.

In Figure 4 the curve marked "estimated minimum weight of battery systems" is drawn using the minimum weights of batteries, for any given length of operating time, shown on Figure 18 of WADC TR 53-180 (May, 1953). This is not an attempt to present an authoritative evaluation of battery performance. Rather, it is an attempt to establish the order of magnitude of battery weights required for a given period of continuous discharge, so that the weights of engine-generator sets might be compared with the weights of battery systems. Since the battery performance data are based on discharge at ideal environmental conditions, the weights shown are approximately the minimum attainable. In many types of environmental conditions, the battery weights would be much greater than shown, and of course there would be some extremes of environments in which the batteries would not function satisfactorily, regardless of the weight of the system. The size of batteries may be estimated rather accurately using an average specific volume of 18 cu in. per lb.

From Figure 4 it is apparent that for less than 1-1/2 hours of operation a battery is lighter than any of the engine-generator sets presently visualized as feasible. At continuous operation for periods longer than 20 hours, an engine-generator set could weigh as little as 1/3 to 1/20 of the weight of a battery system. Between one and 20 hours there is some question as to which is the lighter system depending upon the requirements which must be met. For a manually operated and adjusted set of 200 to 300 watts capacity, the engine-generator set might be preferred over batteries for periods of continuous operation in excess of two to three hours. For the same capacity system which would necessitate a high degree of reliability, automatic starting and unattended operation in adverse environmental conditions, batteries might be lighter unless continuous operation in excess of six hours was required.

With smaller capacity power sources of 35 to 75 watts, the breakeven points corresponding to the larger systems just mentioned would probably be about five hours and 15 hours, respectively. If the power demand is intermittent instead of continuous, the breakeven points would come at a greater number of hours. Similarly, if the electrical load is fluctuating between rated capacity and only a fraction of rated load, with considerable operation at fractional load, the breakeven points would be at a much greater number of hours. Battery performance generally improves with intermittent loading and with outputs at fractional current ratings. In contrast, the fuel consumption and control characteristics of miniature engine-generator sets are such that the over-all weight and size of equipment would be about the same for fluctuating loads as it would be for a continuous load equal to the maximum of the fluctuating load at rating. An intermittent load, with a considerable period between power demands, would impose another severe handicap on the engine-generator set. Then, provision would have to be made to stop the set and to start it again at the proper time. If the starting and stopping were to be automatic and unattended, the weight and size of the starting system would have to be quite large to achieve even reasonable reliability. It is unlikely, for this latter type of operation, that an engine-generator would ever be the preferred power source.

Figures 5 and 6 have been prepared to give a ready picture of the breakeven points just discussed. Since these figures represent estimates of the performance of power plants yet to be developed, based on extrapolation from meager data of the present, they are intended to serve only as a guide for estimating purposes. It is recognized that for each application there may be unusual requirements for the power source which would alter these predictions. However, the curves should be useful for establishing the types of power sources which should be given further consideration.

Gasoline will give the most satisfactory performance for most engine-generator applications. For the smaller size units, or for short periods of operation, use of liquefied petroleum gases (LPG) might make a superior power source. These aspects are discussed more fully in Section 4.4.1.

No comparison has been made here with the sizes and weights of chemical turbine systems and other types of power sources, since these are complex systems in themselves and it was not within the scope of this contract to make such a comparison.

2.4 TYPICAL ENGINE PERFORMANCE

This section is presented to give a summary of the performance characteristics which can be expected in a well-developed miniature engine. There is no intent to imply that the data presented here represent the ultimate that can be achieved in such engines. Neither is it implied that it might not be advantageous to design an engine more conservatively and not push the power outputs to the values presented here. However, so that a fair estimate may be had of what should be attainable from equipment of this type, the optimum test results from many hours of test work on several different engines are presented.

Figures 7, 8, 9 and 10 show the optimum performance which was obtained from all test work with several different types of experimental engines. Performance curves from many different tests were plotted. Then, envelope curves were drawn which included the optimum performance from all of the tests, to obtain the data for Figures 7, 8, 9, and 10. Since these different engines were not necessarily developed to the same degree, it is possible that somewhat better performance could be attained with each of these types of engines. Possibly the L-head engine performance could be improved more than the other types. More extensive development might improve the specific fuel consumption values for each of the engines, although considerable development effort was devoted to reach values as low as reported by these curves. For the purposes of predicting potential performance, for writing specifications, or for preliminary design, it would be optimistic to assume that much improvement in performance over the values reported here could be achieved, unless a long and carefully conducted development program on a specific type of engine were anticipated.

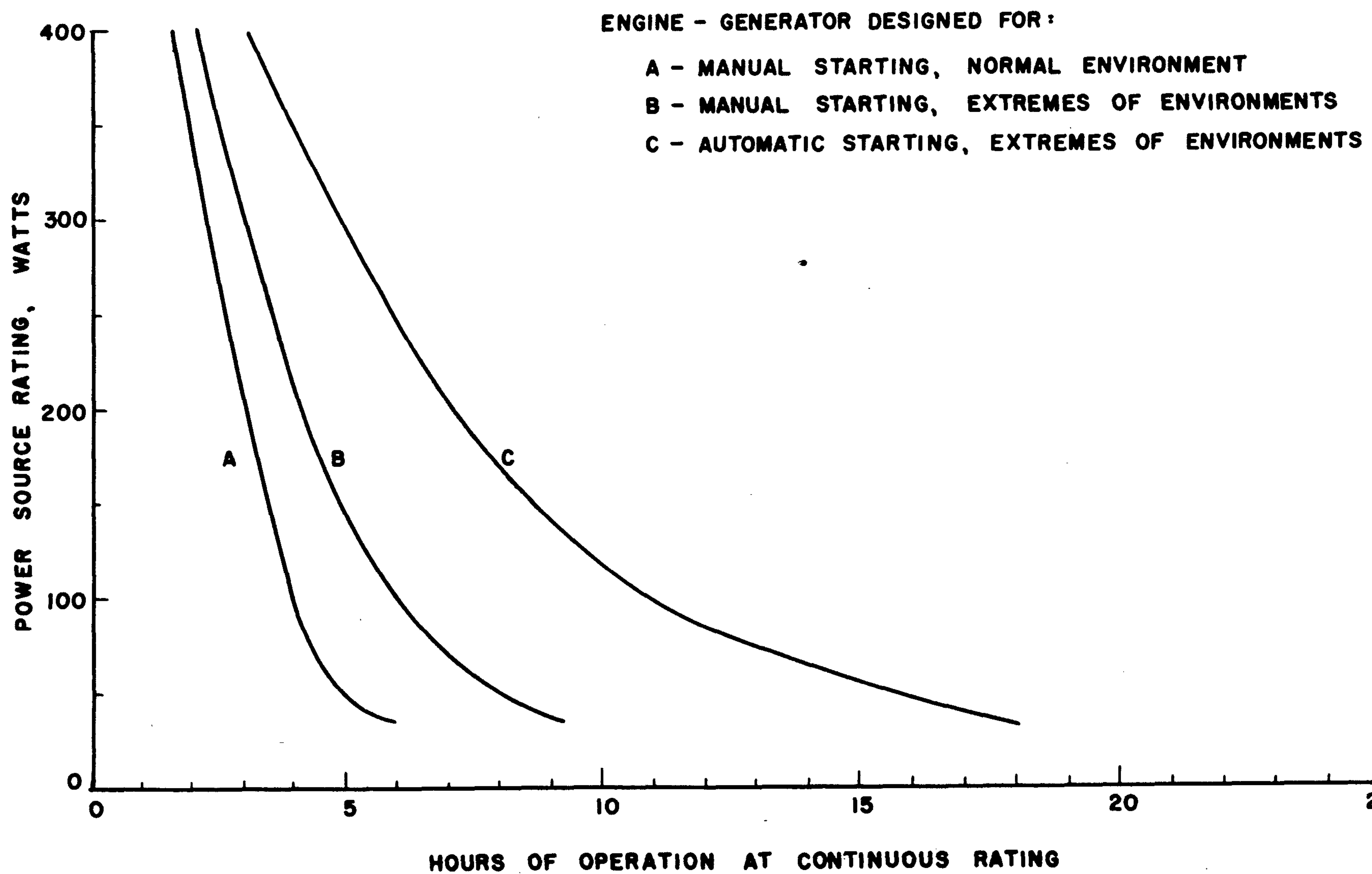


Figure 5. Approximate Operating Time When Battery Weights Exceed Engine-Generator Set Weights

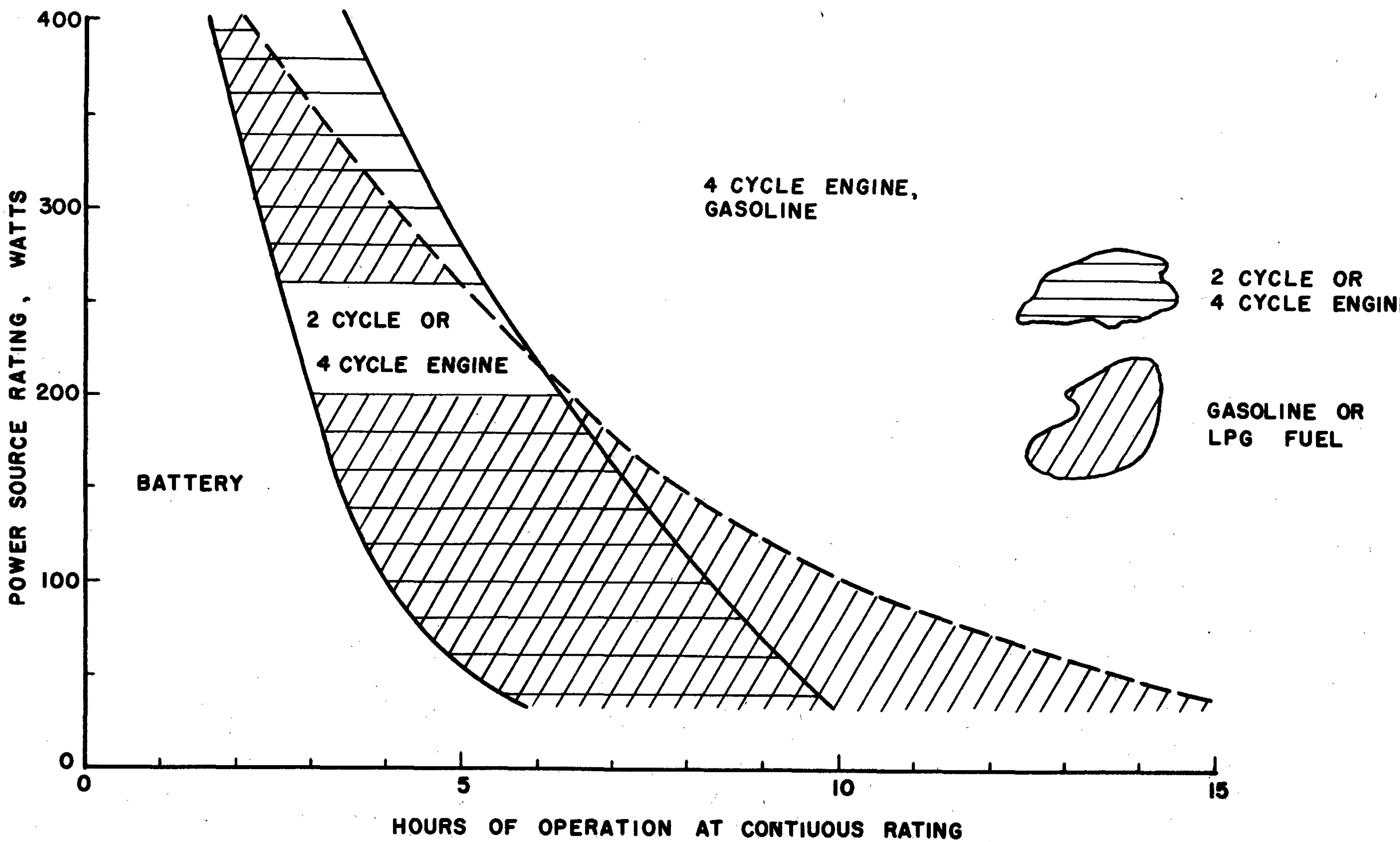


Figure 6. Types of Power Source and Fuel Which Should Be Considered For Various Ratings and Lengths of Operating Time

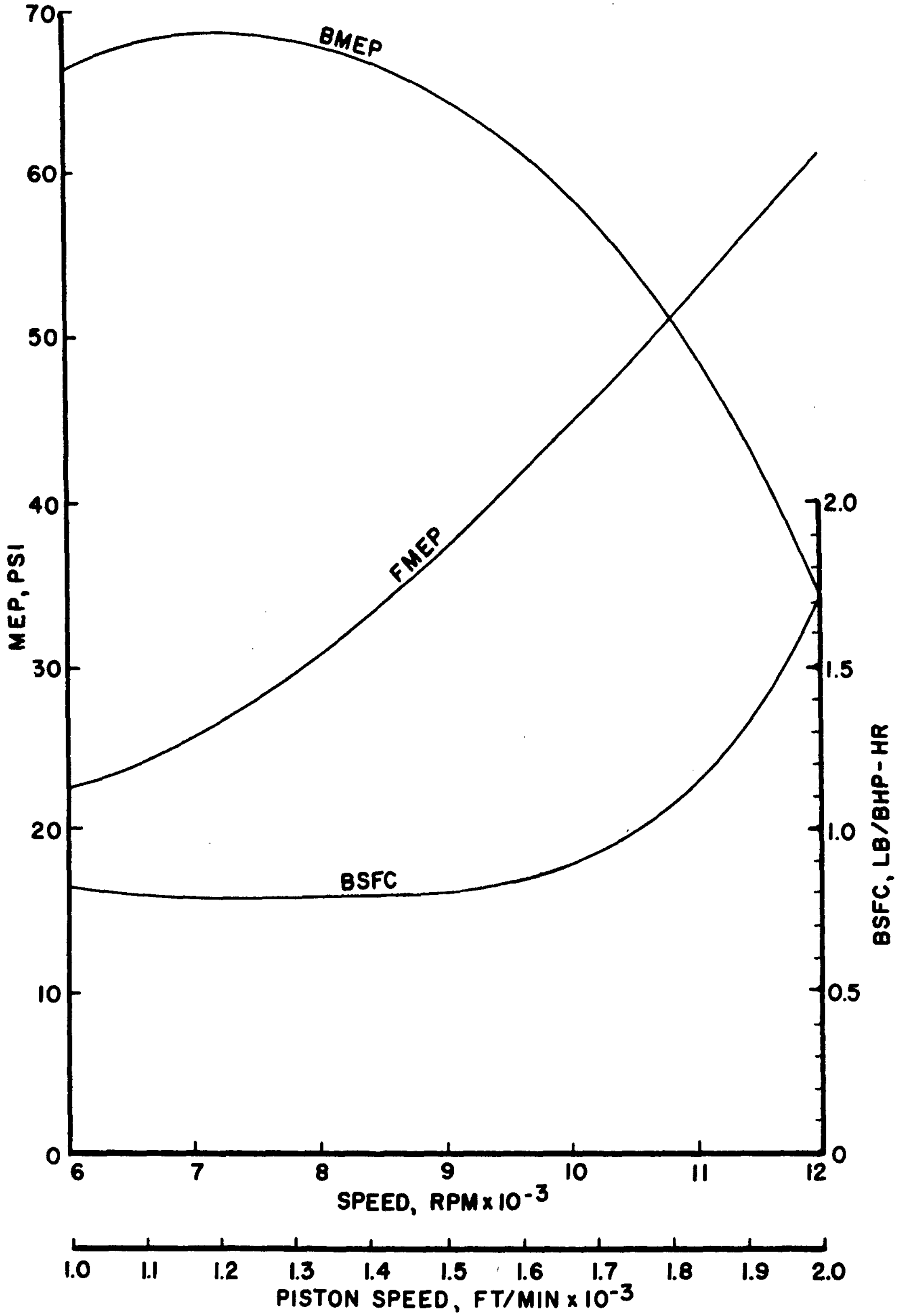


Figure 7. Envelope Curves for Performance of L-Head Four-Cycle Test Engine with 80 Octane Gasoline

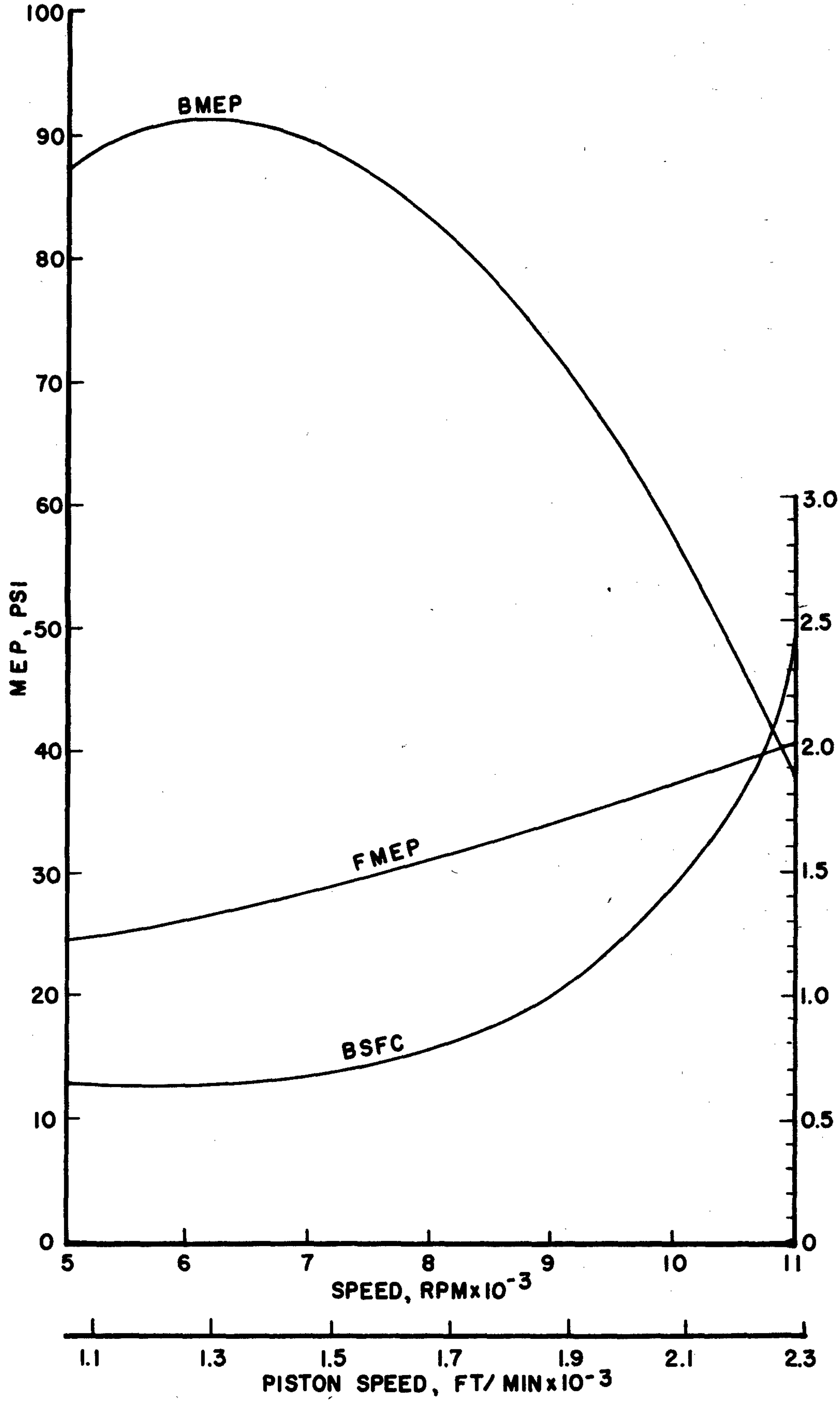


Figure 8. Envelope Curves for Performance of Overhead-Valve Four-Cycle Test Engine with Petroleum Fuels

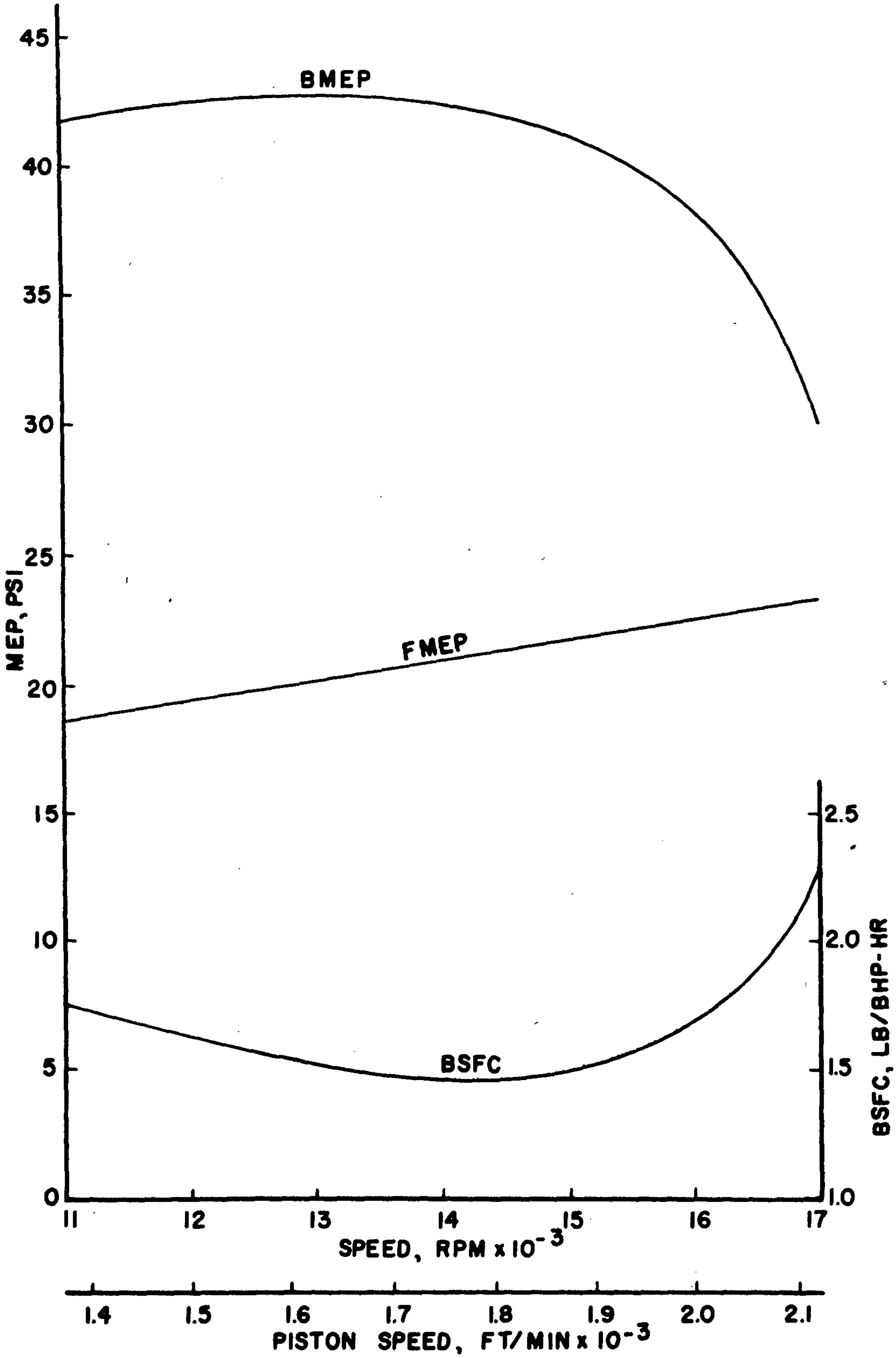


Figure 9. Envelope Curves for Performance of Cross-Scavenged and Loop-Scavenged Two-Cycle Test Engines Using Petroleum Base Fuels and Lubricants

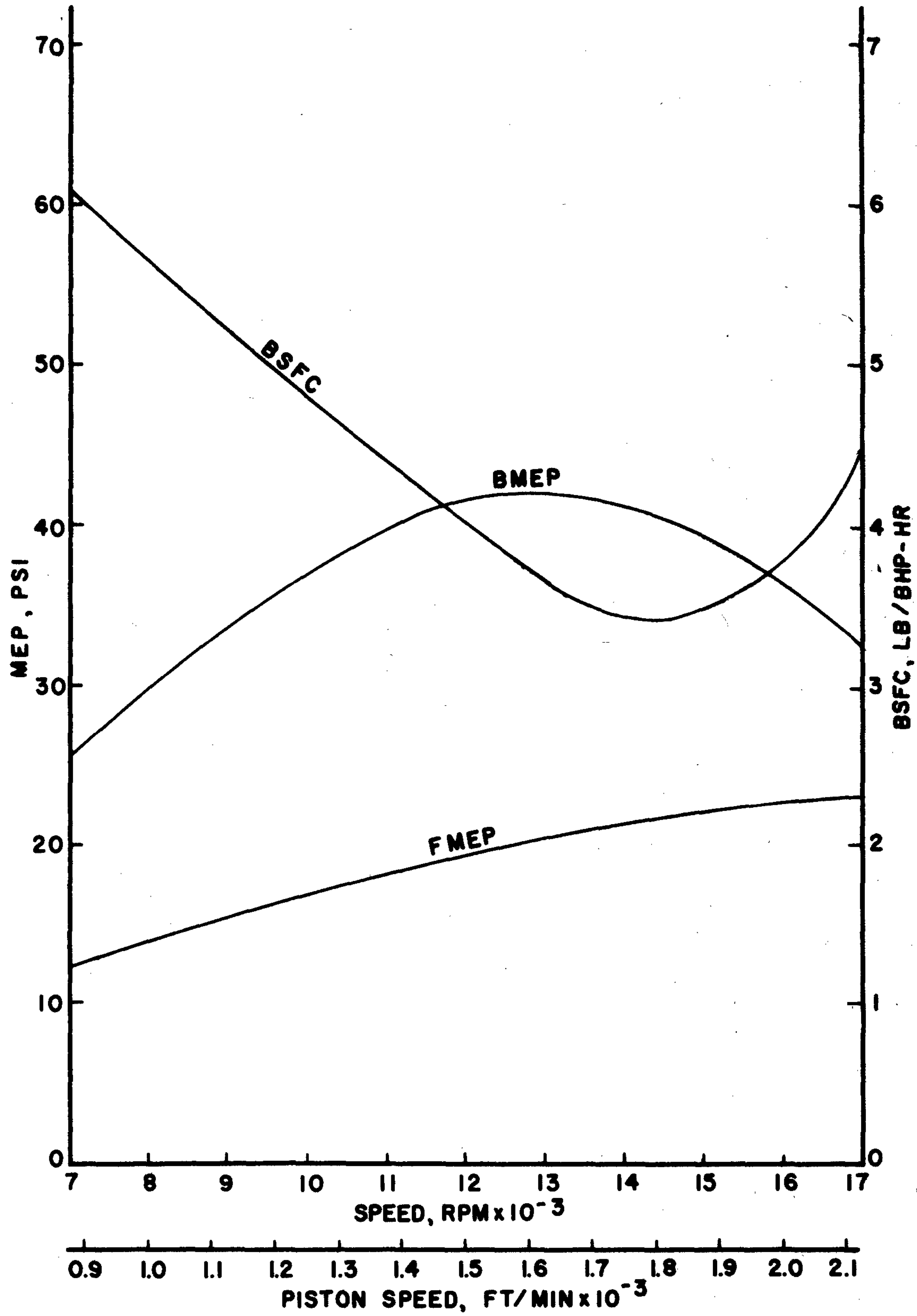


Figure 10. Envelope Curves for Performance of Cross-Scavenged Two-Cycle Test Engine Using Methanol Base Fuel and Castor Oil Lubricant

2.4.1 Four-Cycle Engines

The performance characteristics of three different experimental models of four-cycle engines are presented in Figures 7 and 8. The first figure shows the optimum performance data of an L-head type of engine. The second shows the best performance obtained with two overhead-valve engines. One of these engines was a modified engine sold commercially for use in model boats; the other was an experimental model designed and constructed as a part of the work of this project. It will be noted that the speed range for these engines was between 5,000 and 12,000 rpm. With each engine, though, the best speed for continuous operation was between 6,000 and 9,000 rpm. Inertia forces on the valve mechanism make operation somewhat erratic at the top speed range shown in the curves. At speeds of 6,000 to 9,000 rpm, the bsfc for all three engines was between 0.7 and 0.8 lb per hp hour, using 80 octane aviation gasoline fuel. Each engine had a crankcase sump for lubrication, so that the fuel was not diluted with lubricating oil, as is the practice with two-cycle engines. Tests at part throttle, showed that the fuel consumption on the four-cycle engines can be maintained at 0.7 to 0.8 lb per hp-hr down to one-half load or less. Thus, engines could be designed oversize for reserve capacity, and still maintain a good specific fuel consumption at operating conditions. With this fuel consumption, the brake thermal efficiency of the engine is approximately 18 per cent. The lower bmep values shown for the L-head engine indicate the superiority of the overhead-valve engines, although no great effort was made to improve the breathing capacity of this particular experimental L-head engine. Therein may lie some of the difference in the bmep values shown. The overhead valve design inherently has better breathing, of course, and this is reflected in the results. In Figure 7 the bmep is 68 psi at 7,000 rpm. At this speed the mechanical efficiency of the engine is 73 per cent. Figure 8 shows the bmep at 7,000 rpm is 88 psi, and the mechanical efficiency is calculated to be 76 per cent. In both curves, the friction mean effective pressure rises rather rapidly at the higher speeds, reflecting some increased power required to drive the valve mechanism at these speeds. The above performance was obtained with a 1.53 cu in. displacement engine which gave a maximum power output of 1.1 hp, or a specific power output of 0.7 hp per cu in. of displacement. The other overhead valve engine had a displacement of 0.55 cu in. It yielded a maximum of 0.65 hp, or 1.2 hp per cu in. The L-head engine produced a maximum of 0.6 hp from 0.81 cu in. of displacement, or 0.74 hp cu in. More information pertaining to the design characteristics of these experimental engines may be obtained from References 1 and 2. While no direct operating experience was obtained with smaller sizes of four-cycle engines, it is unlikely that engines much smaller than these could be made to develop as high a hp per cu in. displacement or as low a specific fuel consumption. Engines with two or three times the displacement of these experimental models would likely have about the same performance as shown in Figures 7 and 8. With the larger engines, particular care would be required in the design of the valve mechanism, if good performance at speeds as high as 8,000 rpm is desired. Good operation of miniature four-cycle engines at speeds much over 10,000 rpm does not seem attainable with present design techniques.

2.4.2 Two-Cycle Engines

It will be noted from the curves that the miniature two-cycle engines could be operated at speeds up to 17,000 rpm. This was attained with both cross-scavenged and with loop-scavenged types of design. However, at these speeds, the engine performance was extremely sensitive, and small changes in carburetion setting, spark setting, lubricant type, lubricant temperature, etc. would result in an appreciable change in rpm or in net power output. It will be noted that the bmep curve drops off very rapidly at the higher speeds, indicating both an increase in engine friction and a sharp decrease in the breathing capacity of the engine. In miniature sizes, it is not likely that greatly improved breathing characteristics will be developed. Hence, it is recommended that design speeds of about 12,000 rpm would represent the maximum for rating purposes. The bmep will be somewhat over 40 psi for petroleum base fuels, but may vary between 30 and 40 psi for alcohol base fuels. Test results seem to indicate that the friction may be slightly less with the alcohol-castor oil mixture than for gasoline-paraffin base oil mixtures, although the mechanical efficiency for the two-cycle engines at 12,000 rpm is 70 per cent, for both types of fuel mixtures. All test results seemed to indicate that mechanical efficiency values of 60 to 75 per cent were common with miniature reciprocating engines. Test experience shows that the design of the engine must be kept as simple as possible, to avoid excessive friction drag on the power output and to eliminate sources of engine failure.

Brake specific fuel consumption values just under 1.5 lb per bhp-hr were attained with petroleum fuels, in both the cross-scavenged and the loop-scavenged designs of two-cycle engines. In general the loop-scavenged engine gives slightly better fuel consumption than the cross-scavenged design, but when the latter is properly designed and adjusted, the difference is not appreciable. The petroleum-based fuel used most commonly in this test work consisted of 90 per cent by volume of 80 octane aviation gasoline and 10 per cent oil having a viscosity of SAE No. 70. When alcohol base fuel was used, the minimum bsfc achieved was about 3.5 lb per hp-hr. The alcohol mixture found most suitable consisted of 80 per cent by volume of methanol and 20 per cent castor oil. In all tests the total weight of the fuel plus lubricant mixture was used in calculating the lb of fuel admitted to the engine.

While some improvement in fuel consumption might be attained with an extensive development program, it is unlikely that miniature, high-speed, two-cycle engines will achieve much better fuel economy than about 1.5 lb per hp-hr. This represents a thermal efficiency of 9 per cent for the petroleum-based fuel. The brake thermal efficiency with methanol-base fuel is about 7.5 per cent.

These test data were obtained with several model engines of the model aircraft type and with three experimental engines designed specifically to serve as test vehicles for miniature-engine performance studies. The two engines which showed the best performance, and hence provided most of the test points for the envelope curves, were a cross-scavenged engine having a displacement of 0.61 cu in. and a loop-scavenged engine with a displacement of 0.47 cu inch. The former yielded a maximum power output of about 1.0 hp, or a specific power output of 1.6 hp per cu in. of displacement. The latter developed approximately 0.7 hp at peak power operation, or a similar 1.5 hp per cu in. of displacement. All tests of this type were conducted at laboratory conditions, with approximately 75°F air temperature and a barometric pressure of about 29.5 in. Hg. Results obtained from tests of smaller size engines showed lower bmep values and higher bsfc values than those reported in Figures 9 and 10. Tests of two-cycle engines having two to three cu in. displacement showed that reasonable bmep values were still about 40 psi. Some two-cycle engines fo six to ten cu in. displacement develop up to 60 psi bmep. Fuel consumption of these larger engines remains at about 1.5 lb per hp-hr, although some manufacturers report somewhat lower bsfc values.

2.5 STARTING AND OPERATION IN EXTREMES OF ENVIRONMENT

Altitude and low temperature performance tests were conducted to determine the feasibility of operation for a miniature engine-generator set at extreme environmental conditions. Information concerning these effects was obtained for both two-cycle and four-cycle engines. The four-cycle engine used was the L-head model described in Table 2 from WADC TR 53-180, "Study of Miniature Engine-Generator Sets, Part II." The two-cycle engines used were the Ruckstell-Hayward Pockette and the Mark III engines, both described in WADC TR 53-180, "Study of Miniature Engine-Generator Sets, Part IV." A brief summary of the results of the altitude and low temperature performance tests is given below. For more detailed information, consult WADC TR 53-180, "Study of Miniature Engine-Generator Sets, Part IV."

2.5.1 Altitude Performance

Tests were conducted with the engines described above to determine the limits of both starting and operation at high altitudes. For high-altitude operation it was found that a carburetor setting giving a slightly lean mixture at ground-level conditions resulted in the best performance.

The L-head four-cycle engine was tested using both 80-octane aviation gasoline and methyl alcohol as fuels. Using aviation gasoline, the engine was able to start up to an altitude of 9,000 feet and was capable of operating successfully at altitudes up to 22,000 feet. With methyl alcohol, the engine could start as high as 8,000 feet and operate to the equivalent of 15,000 feet.

The Mark III, two-cycle engine was able to start up to a point equivalent to 11,000 feet using a mixture of 90 per cent aviation gasoline and 10 per cent SAE No. 20 lubricating oil as a fuel; it was capable of sustaining operation to an altitude of 14,000 feet with this fuel. With a fuel consisting of 90 per cent methyl alcohol and 10 per cent castor oil, it was able to start at 14,000 feet and was capable of operating to 17,000 feet. The Ruckstell-Hayward Pockette two-cycle unit was operated only on the gasoline-oil mixture and was capable of operation up to 15,000 feet.

These results indicate that four-cycle engines will give slightly better altitude performance than the two-cycle engines. Since the lack of air is the primary reason for the engine to cease operating at high altitudes, the positive displacement scavenging of the four-cycle engine becomes exceedingly important.

2.5.2 Low-Temperature Performances

Performances of miniature engines in cold environments have been analyzed to determine the effect of reduced temperature upon engine operating characteristics and ease of starting. Tests with various engines have indicated that the power input is unaffected or increased slightly by decreasing temperatures. This is largely due to the fact that the increased air density at cold temperatures makes engine breathing easier. Other possible operating difficulties, particularly those involving carburetion, are minimized owing to the fact that the single-cylinder engine has reduced fuel distribution problems. Thus, the operation of miniature engines at cold temperatures seems very feasible.

The starting of miniature engines in a cold environment presents many problems, however. Basically, the most important single factor in limiting the ease of starting is the inherent problem of volatilizing and distributing the fuel. The problem becomes more difficult as the environmental temperature is lowered.

Two variables must be considered in attempting qualitatively to describe ease of starting. One variable is the length of time the engine is cranked over before it starts; the other is the speed required to crank the engine over to insure starting. It has been determined that the latter, that of engine cranking speed, is by far the more important.

The relative ease of starting was studied using the L-head, four-cycle engine and the Mark III, two-cycle engine. The basic fuels used in these tests were aviation gasoline and methyl alcohol. Necessary cranking speed was plotted as a function of temperature to determine ease of starting. Such curves as determined for the L-head engine using both fuels are shown in Figure 11.

These curves represent the best data obtainable for each of the two fuels, using optimum choke settings. As can be seen, the difficulty of starting increases rapidly as ambient temperature is decreased. Also, the engine starts more easily with aviation gasoline than with methyl alcohol. This is ascribed to the fact that, although methyl alcohol has a lower boiling point than gasoline, its latent heat of vaporization is over three times as great. This results in severe cooling of the intake manifold which increases starting difficulty.

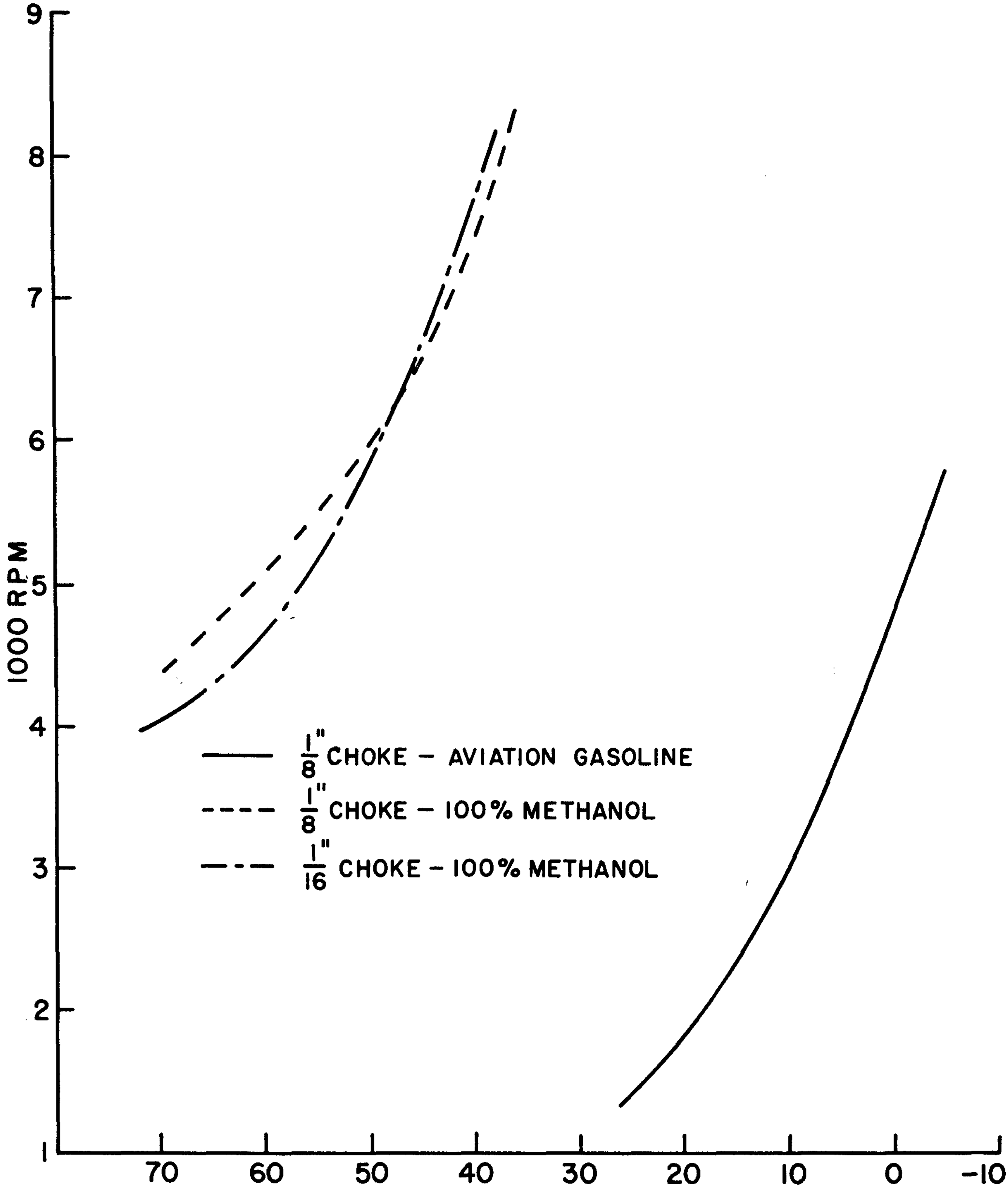


Figure 11. Use of Methyl Alcohol as a Fuel Compared With That of Aviation Gasoline

Other difficulties encountered in cold starting tests were: (1) the necessity of providing a method of automatic control to decrease the amount of choking immediately after starting and (2) the increased cranking torque required by the increased viscosity of common lubricating oils at low temperatures.

Thus, the problem of engine starting at cold temperatures is a severe one, particularly when automatic starting is required. A manual system would impose less rigid requirements since the engine could be pre-heated prior to starting.

2.6 TYPICAL GENERATOR PERFORMANCE

A search of the literature indicated that very little has been written on small, high-speed, dc generators of ratings from 35 watts to 400 watts. Through correspondence and study of technical publications, it appears that some investigations are being made on small ac generators, but most of these are larger than the sizes specified in the contract. Some of them have frequencies higher than the specified range. Thus, generators had to be developed to obtain typical performance and operating characteristics. Three satisfactory dc generators were developed but, because of the limitation of time, only a model of the flux-switch generator was built. These four generators were constructed at The Ohio State University.

It was hoped that a thorough study could be made on the following types of ac generators:

(1) Flux-switch generator
(2) Induction generator
(3) Permanent magnet generator
(4) Inductor generator
(5) Conventional synchronous generator.

Owing to the limited amount of time available for study, only exploratory work was done on the flux-switch, induction, and permanent magnet generators. Industrial activity in the area of small, high-speed, ac generators is, however, progressing and more information should be available from that source.

Figure 12 is a disassembled view of an inductor generator manufactured by the Westinghouse Electric Corporation. Figure 13 shows a permanent magnet generator manufactured by the Ruckstell Corporation in Los Angeles, California. A sketch of the flux-switch generator will be given in the discussion of this generator. Photographs of the induction generator and the permanent magnet generator (Phelon generator) will be included in the materials on these two generators.

Except for the conventional synchronous generator, the ac generators do not utilize brushes and slip rings. In the absence of moving contacts. radio interference from this cause is eliminated.

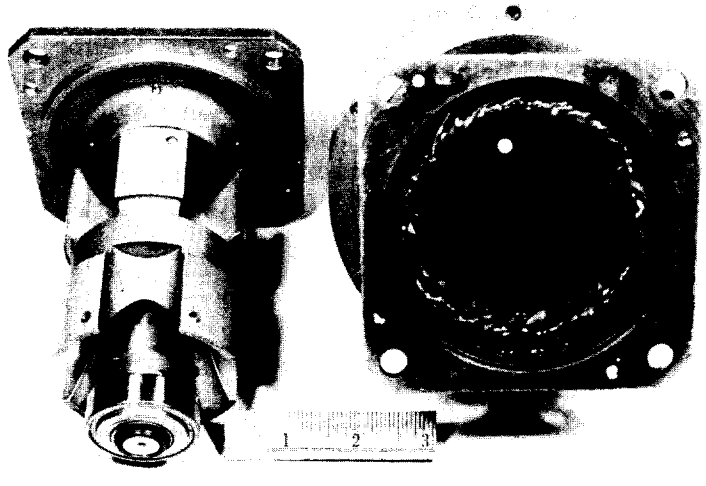


Figure 12. Inductor Generator. 1.2 KVA, 3 phase, 120/208 Volts, 400 Cycles, 6,000 rpm. Manufactured by the Westinghouse Electric Corporation

Figure 13. Permanent Magnet Generator. 0.15 KVA, 3 phase, 69/120 Volts 800 Cycles, 12,000 rpm. Manufactured by the Ruckstell Corporation in Los Angeles, California

No altitude tests and no life tests have been performed on the tested generators. Also, the generators have not been tested for maximum safe speed and for maximum safe temperature. In general, from observation of test performances, the dc and ac generators should be fairly reliable for speeds less than 15,000 rpm and for altitudes less than 22,000 feet.

Brief descriptions and test data of the tested generators will now be presented. It must be remembered that all testing was conducted at ground level conditions and at an ambient temperature of approximately 25°C.

2.6.1 DC Generators

Three dc generators were developed at The Ohio State University with power ratings of 150, 200 and 400 watts. They were 120-volt, flat-compounded, two-pole, lap-wound, approximately 12,000 rpm machines with efficiencies ranging from 50 to 57% (including internal cooling fans). These generators were developed primarily for the development of the design manual of small high-speed dc generators which was reported in "Study of Miniature Engine-Generator Sets, Part III, Design Procedure of Small High-Speed DC Generators" WADC TR 53-180, March 1956.

Typical terminal voltage versus load current curves of the 400-watt, 12,250 rpm generator are shown in Figure 14. It should be noted that there is a slight difference between the short-shunt and long-shunt connections, with a preference towards the short-shunt connection. Other typical curves of the 150-watt and 200-watt generators are given in the above technical report, WADC TR 53-180, March 1956.

From studies to date, it appears that satisfactory dc generators can be developed from the design manual within the range of 35 watts to 400 watts. The problem of brush wear at altitudes less than 22,000 feet (seemingly, the present limitation of engine operation) should not present too much difficulty.

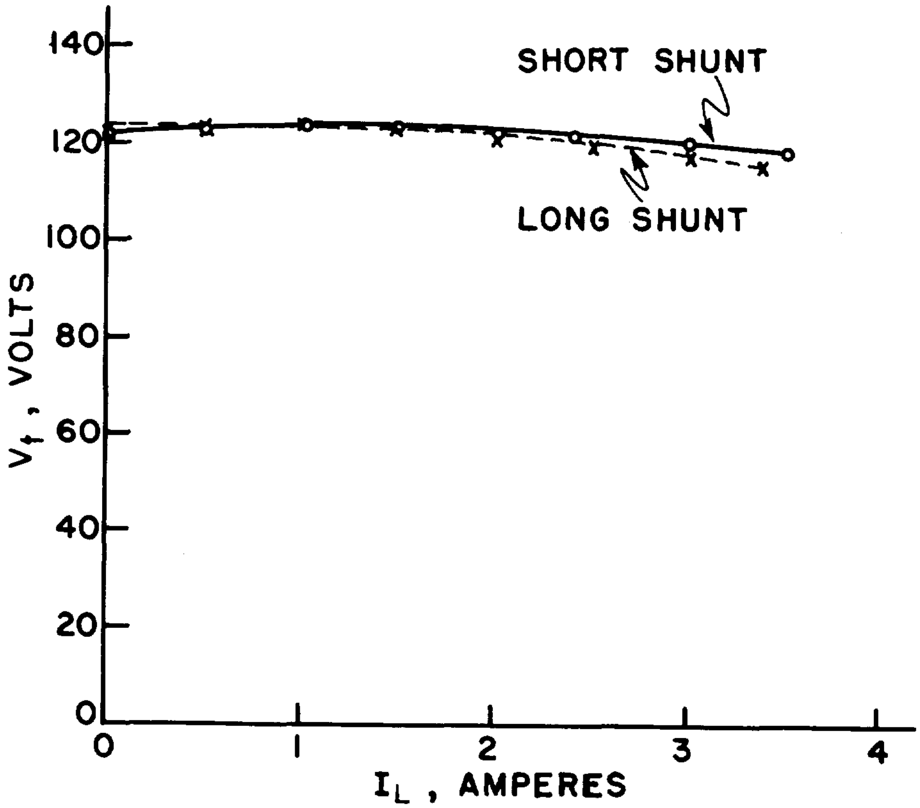


Figure 14. Terminal Voltage vs. Load Current Curves for a 400-Watt, 12,250 rpm Generator

2.6.2 Flux-Switch Generator

A sample single-phase flux-switch generator was built at The Ohio State University using the stator and rotor laminations furnished by The American Machine and Foundry Company, Pacioma, California. The use of these laminations was a matter of convenience to start the study, and the merits of these laminations will depend on test performance when compared with other configurations.

To illustrate the flux-switch principle, sketches of the sample electro-magnetic, flux-switch generator are shown in Figure 15. The flux paths in Figure 15, which are shown by arrows, indicate an upward flux direction in both armature windings. When the rotor has moved to the position shown in Figure 15, the flux linkage through the armature coils has been reversed. Thus, the armature flux linkage of the flux-switch generator varies between equal positive and negative magnitudes in contrast to the unidirectional flux change which takes place in the more conventional inductor alternator. This difference in armature flux changes will, in general, give an advantage to the flux-switch generator over the inductor generator from the standpoint of power output. It

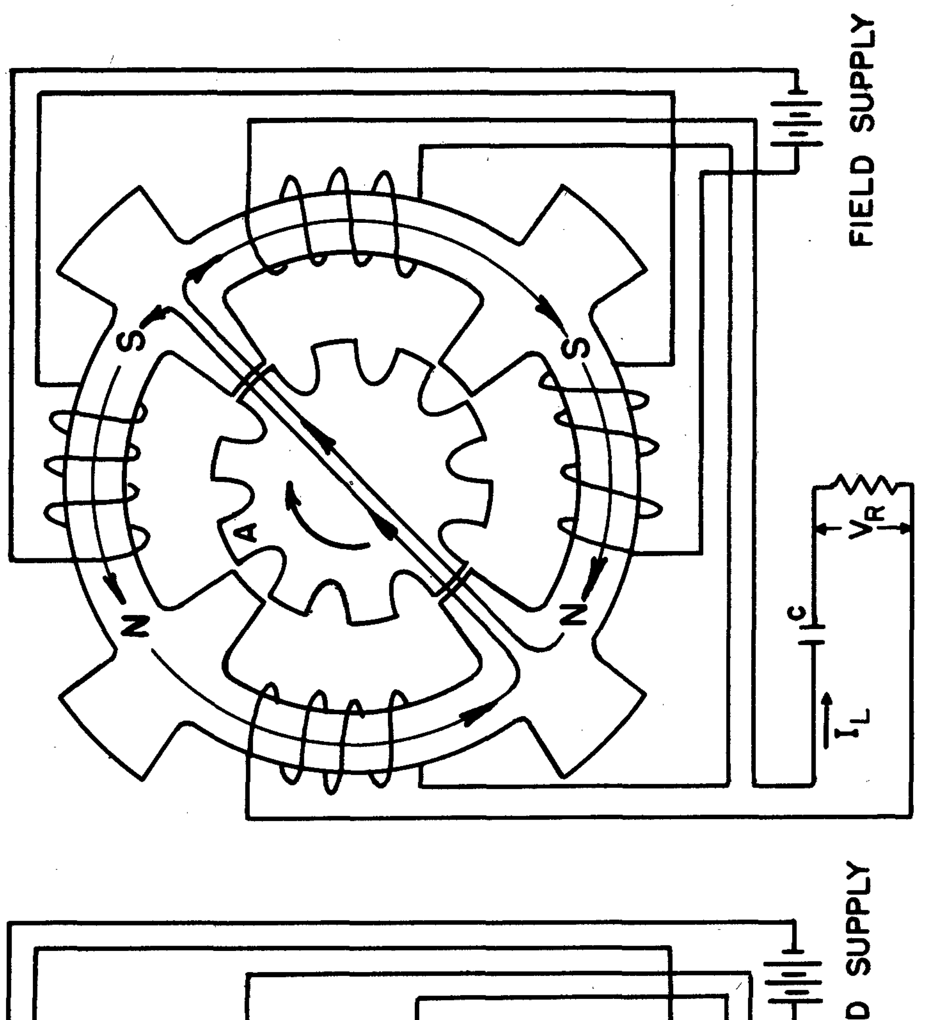


Figure 15. Sketch of an Electro-Magnetic Flux-Switch Generator

should be noted that the flux-switch generator may have either permanent magnets or field windings for approximately the same basic performance.

Exploratory tests were performed with the single-phase flux-switch generator by driving it at 12,000 rpm which resulted in a 2000 cycle output (it was hoped to study the flux-switch generator for 800 cycle operation). The tests indicate that a series condenser of proper size is necessary, as shown in Figure 15, to keep the load voltage from dropping too rapidly. Two typical load voltage V_R versus load current I_L curves are given in Figure 16.

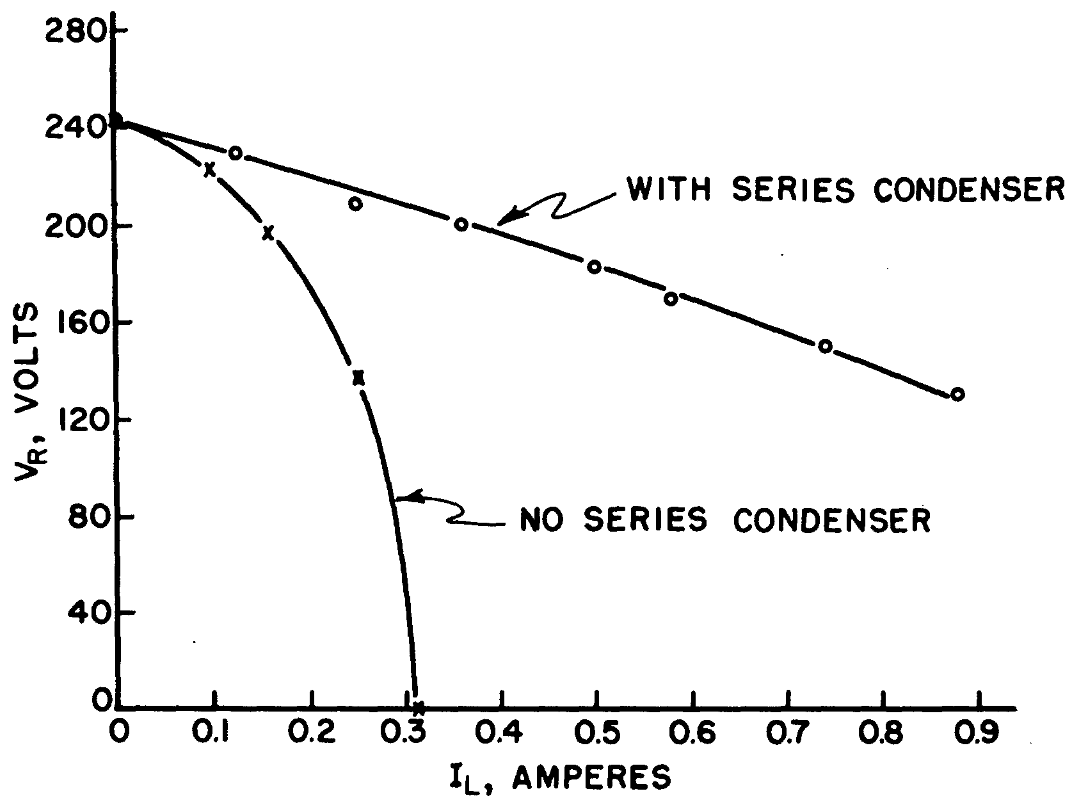


Figure 16. Load Voltage Versus Load Current Curves for an Electro-Magnetic Flux-Switch Generator

Figure 17 shows wave forms of load voltages and load currents. As can be seen from the photographs, the wave forms become more sinusoidal as the load current is increased.

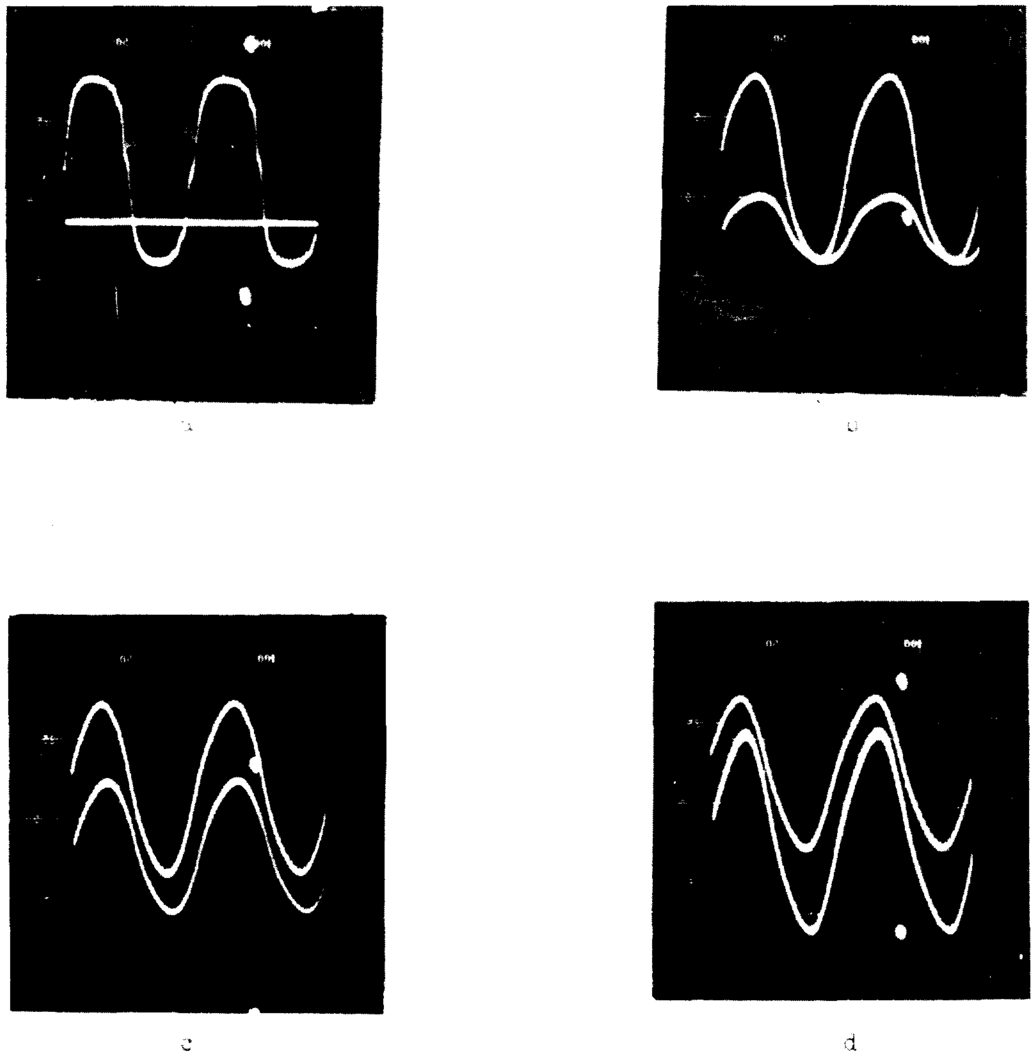


Figure 17. Load Voltage and Current Wave Forms for an Electro-Magnetic Flux-Switch Generator at Various Loads (top curves, voltage wave forms; bottom curves, current wave forms)

	Current, amps	Voltage, volts
a	0	242
b	0.25	210
c	0.5	183
d	0.75	150

2.6.3 Induction Generator

Exploratory tests were performed on an induction generator by capacitive excitation of a squirrel-cage induction motor made by the Rotron Manufacturing Company (see Figure 18a). The induction motor had the following specifications: 0.028 HP, 115 volts, 0.33 amperes, 3 phase, 400 cps, 9000 rpm. The motor was driven at approximately 12,270 rpm to obtain a no-load frequency of 400 cps. Figure 18b shows how the resistive load, series capacitors, and excitation capacitors were connected to the generator terminals.

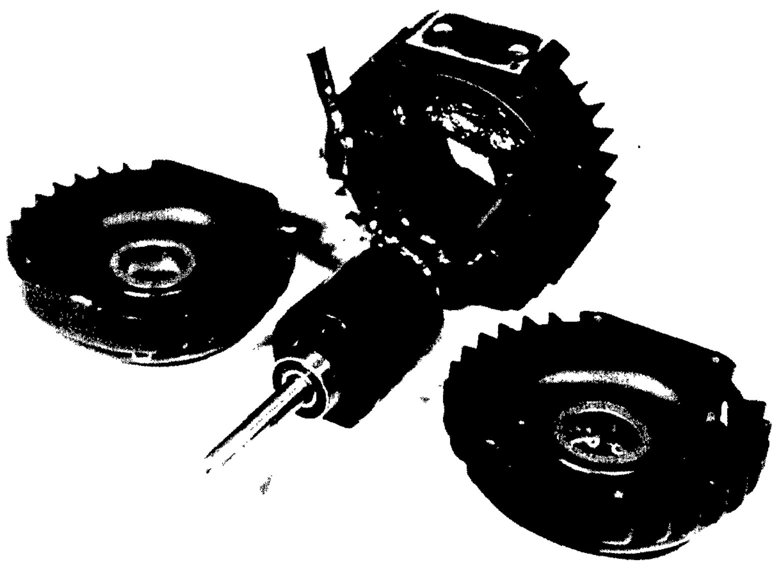


Figure 18a. Squirrel-Cage Induction Motor Manufactured by the Rotron Manufacturing Co.

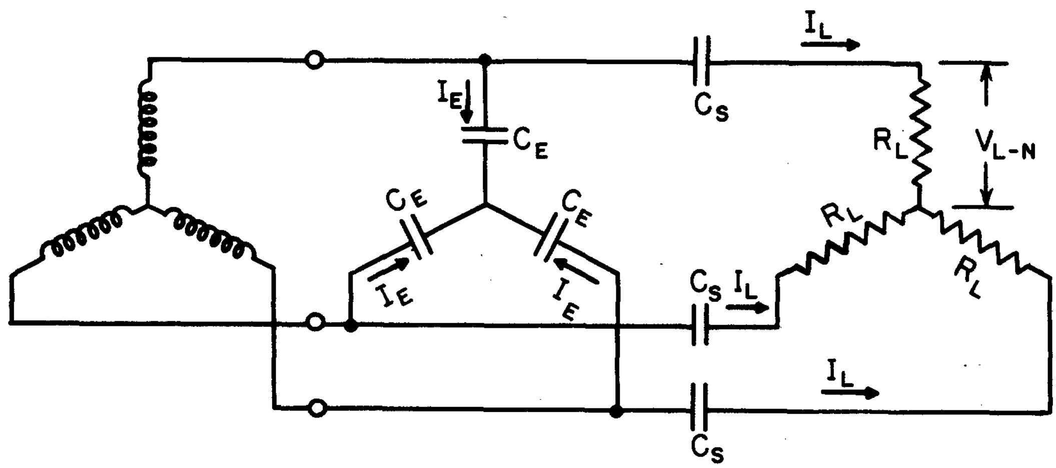


Figure 18b. Diagram Indicating How the Excitation Capacitors, Series Capacitors, and Load are Connected to the Terminals of an Induction Generator

The principle of operation of the induction generator is similar to the dc shunt generator. The induction generator with proper capacitors connected in shunt across its terminals (See C_E in Figure 18b) will build up a voltage. The final build-up voltage is determined by the no-load terminal voltage versus excitation current curve of the machine and the value of reactance X_E of the excitation capacitors. Figure 19 shows the no-load line to neutral voltage versus excitation current curve of the tested generator. As shown in the figure, the no-load voltage V_O is found from the intersection of the no-load voltage curve and the excitation reactance line. For Y-connected excitation capacitors the slope of the excitation reactance line is equal to the reactance of a single excitation capacitor. It should be noted that if X_E is larger than the initial slope of the no-load voltage versus excitation current curve, the generator will not build up a voltage.

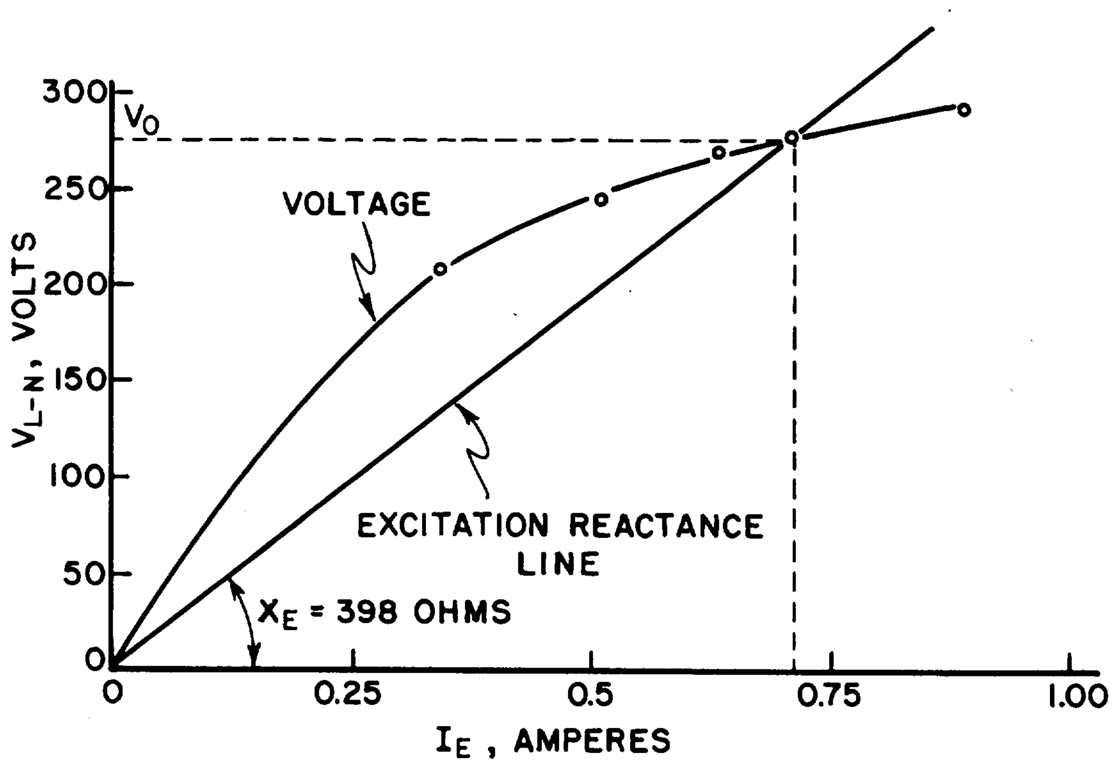


Figure 19. No-Load Line to Neutral Voltage vs. Excitation Current of an Induction Generator

As with the dc shunt generator, a residual magnetism must be present to obtain a voltage build-up. This residual magnetism might have to be restored after a short circuit or after an excessive load. This constitutes a disadvantage of the induction generator when compared with the permanent-magnet generator.

A comparatively high no-load current was required to build up the generator voltage and to maintain fairly good voltage regulation. For the tested generator, as can be seen from Figure 19, the no-load current was equal to 0.71 ampere as compared to the original motor rating of 0.33 ampere. Similar results were also experienced by an electrical manufacturing company when an ordinary induction motor was converted to an induction generator.

Fairly good voltage regulation can be obtained by placing proper capacitors in series with the load. Figure 20 shows voltage regulation curves of the tested induction generator for different values of series capacitors. As can be seen from the figure, the voltage regulation was improved by decreasing the series capacitors.

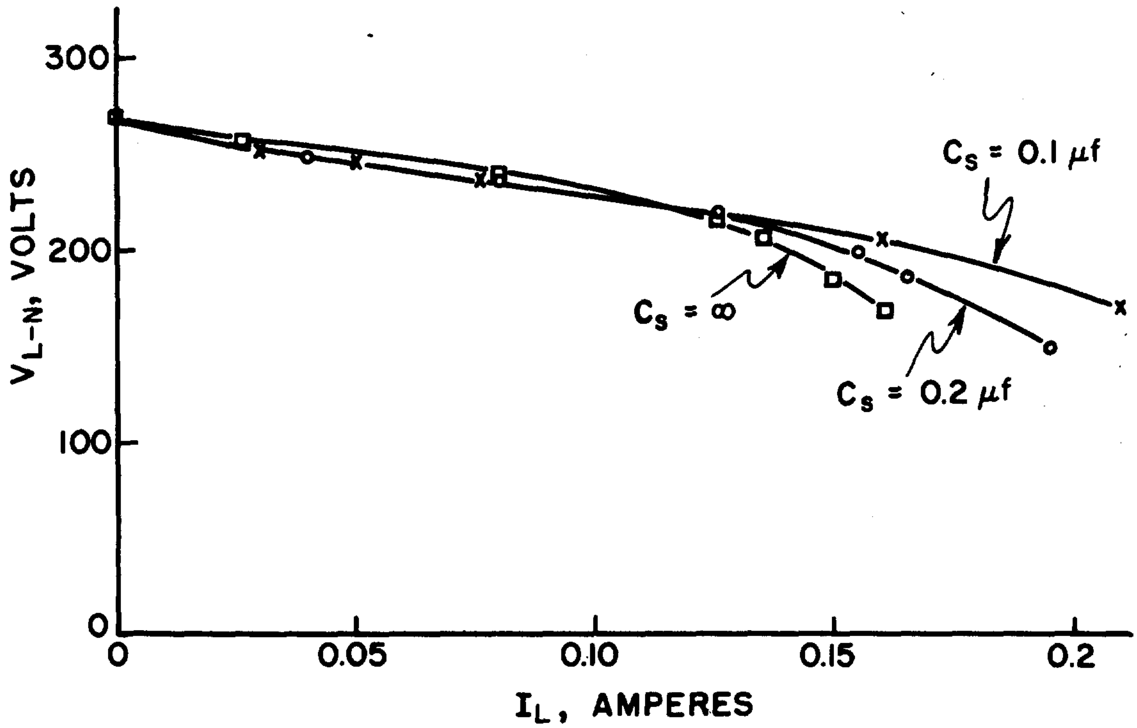


Figure 20. Voltage Regulation Curves for Different Series Capacitors of an Induction Generator

The frequency of the output is directly proportional to the rotor speed plus the slip speed. For induction generators the slip speed (field speed - rotor speed) has negative values. As the load increases the slip speed becomes more negative and therefore causes a frequency drop. If constant frequency is desired, the speed of the prime mover must be increased as the generator is loaded. Such a speed characteristic might require a complicated control system for the prime mover.

An asset of the induction generator is that it produces good sine waves. The wave shape of the tested generator was approximately sinusoidal.

2.6.4 Permanent-Magnet Generators

A series of exploratory tests were performed with a permanent-magnet 400 cps generator which was purchased from the R. E. Phelon Company Incorporated, Springfield, Massachusetts. This generator features a flywheel type of construction wherein the rotor moves outside the stator, resembling a flywheel. The Alnico VI permanent magnets and poles are fastened to the rotor against centrifugal force. Figure 21 shows a disassembled view of the Phelon permanent-magnet generator.

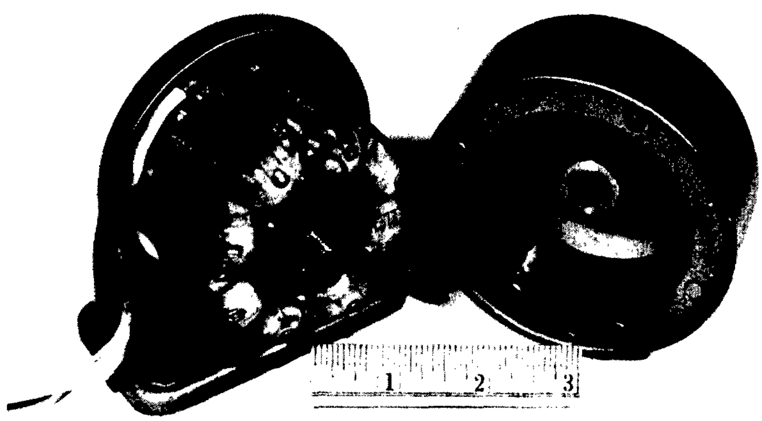


Figure 21. Disassembled View of the Phelon Permanent-Magnet Generator

The tests consisted of operating the generator at 6000 rpm with the following power factor loads:

a. Unity power factor
b. 0.9, 0.8, 0.7 lagging power factor
c. 0.9 leading power factor.

The voltage versus load current curves are shown in Figure 22. For the lagging power factor loads, air-core inductances were used. Attention is called to the 0.9 leading power factor curve (Figure 22), which shows that the terminal voltage rises from the no-load value of 135 volts as the load current is increased. The efficiency curves for the different power factor loads are given in Figure 23.

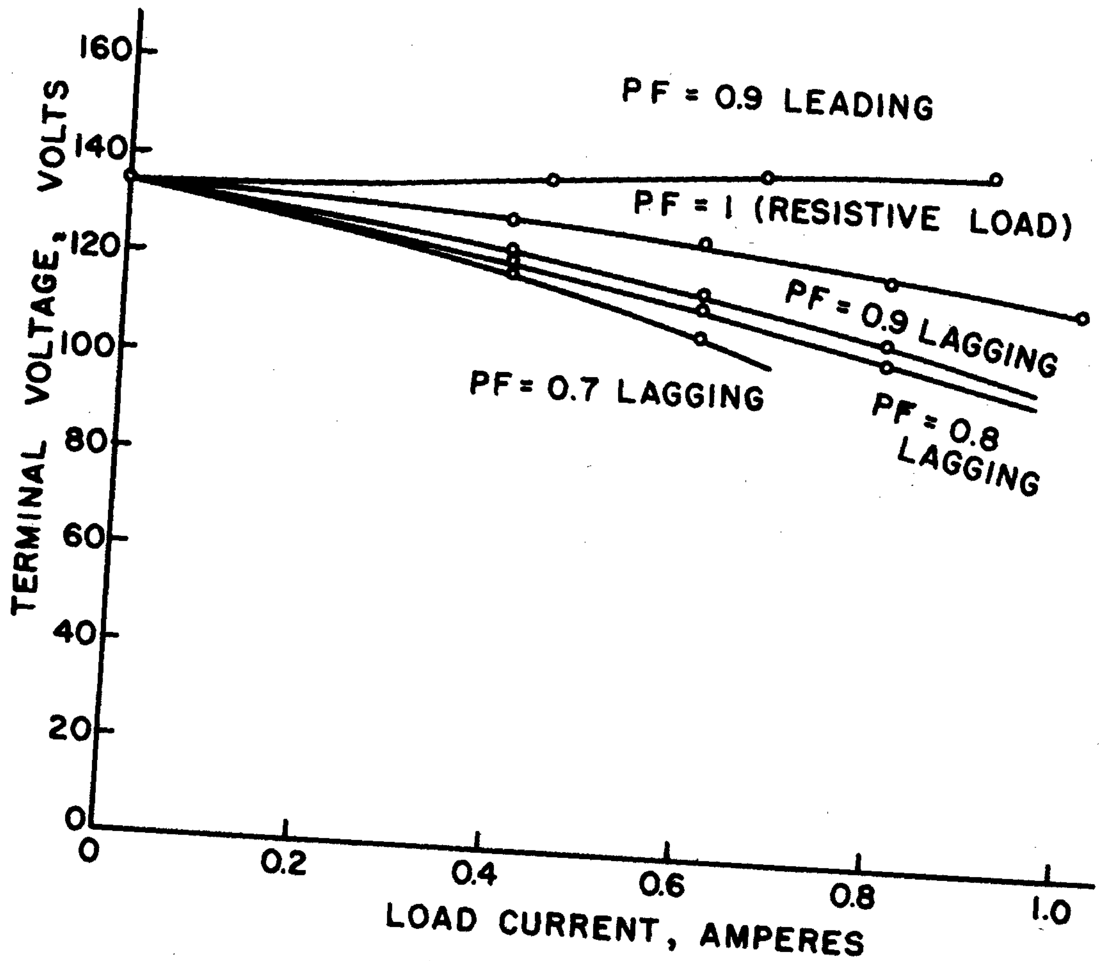


Figure 22. Terminal Voltage Versus Load Current for the Phelan Permanent Magnet Generator

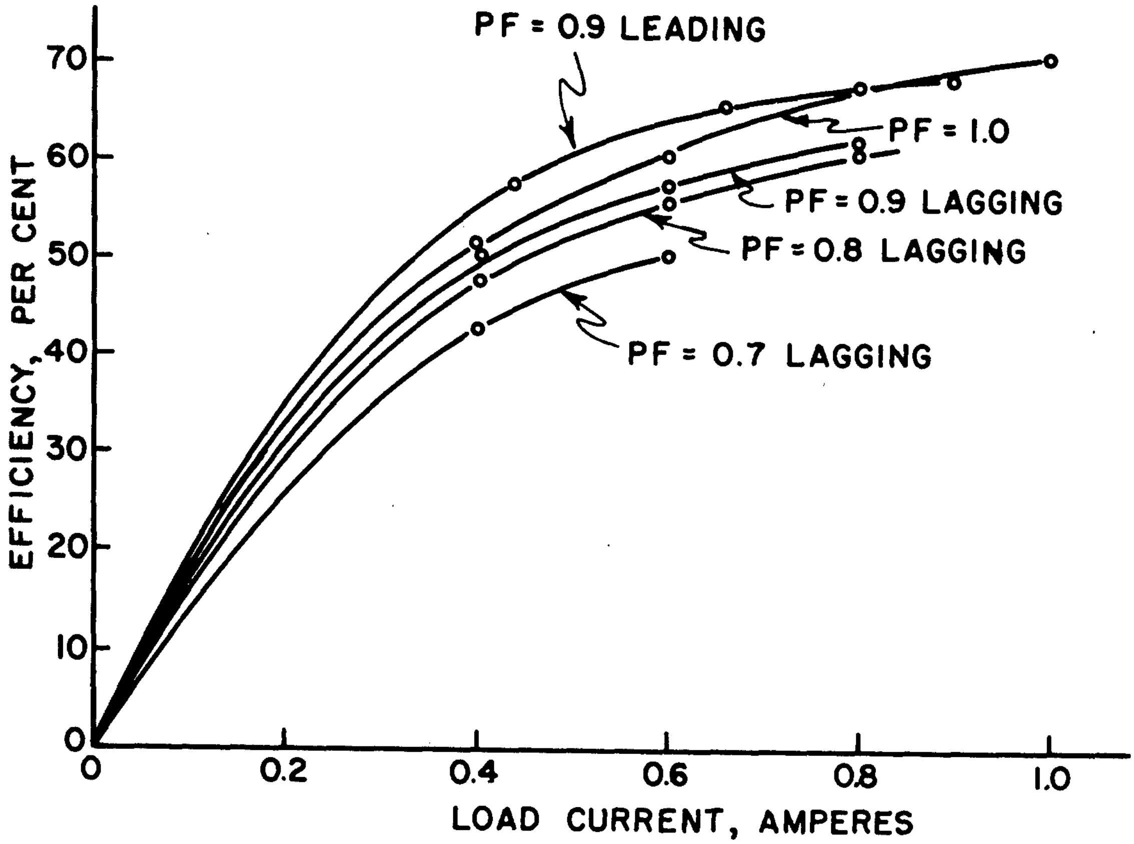
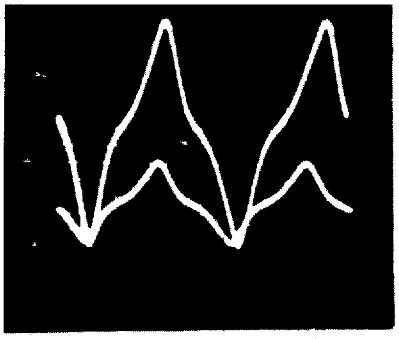


Figure 23. Efficiency Versus Load Current for the Phelon Permanent-Magnet Generator

The voltage and current wave forms deviate from a sinusoid considerably. An important reason for this deviation is that the generator makes use of concentrated windings. Figure 24 indicates the voltage (top curves) and current (bottom curves) wave forms for different power factor loads. It is believed that the wave forms could be improved by using a distributed stator winding.

Test data of another permanent-magnet generator will now be presented. The generator has a rated power output from two separate single phase windings, 75 watts from the high voltage winding and 25 watts from the low voltage winding. The weight, size, and rated output of the generator are given in Tables I and II. This generator was used for the Ruckstell-Hayward Power Supply for Radio Beacon AN/ART-27(XA-1). The tests were performed by the Ruckstell-Hayward Corporation and the data were presented in "Design Study for Power Plant Type   for Use with Radio Beacon AN/ART-27(XA-1)" AF Technical Report No. 6111. For convenience, the data are reproduced in this report.



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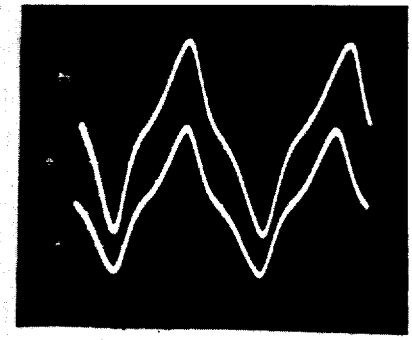

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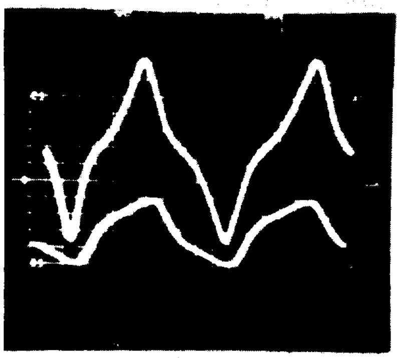

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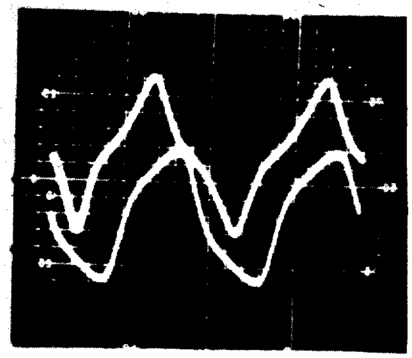

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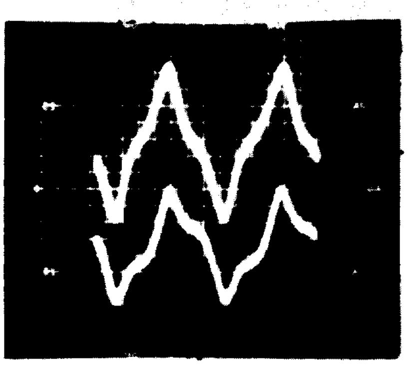

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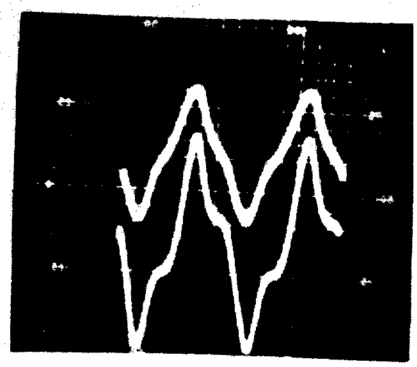

f

Figure 24. Voltage and Current Wave Forms for Phelon PM Generator at Various Loads and Power Factors (top curves, voltage wave form; bottom curves, current wave form)

	P.F.	Current, amps	Voltage, volts
a	1.0	0.40	130
b	1.0	0.80	121
c	0.8 Lagging	0.40	121
d	0.8 Lagging	0.80	104
e	0.9 Leading	0.56	141
f	0.9 Leading	1.11	147

Figure 25 is a disassembled view of the generator. Figure 26 shows the terminal voltages versus load currents for the high and low voltage windings.

Figure 25. Disassembled View of the Permanent-Magnet Generator Used For the Ruckstell-Hayward Power Supply For Radio Beacon AN/ART-27 (XA-1)

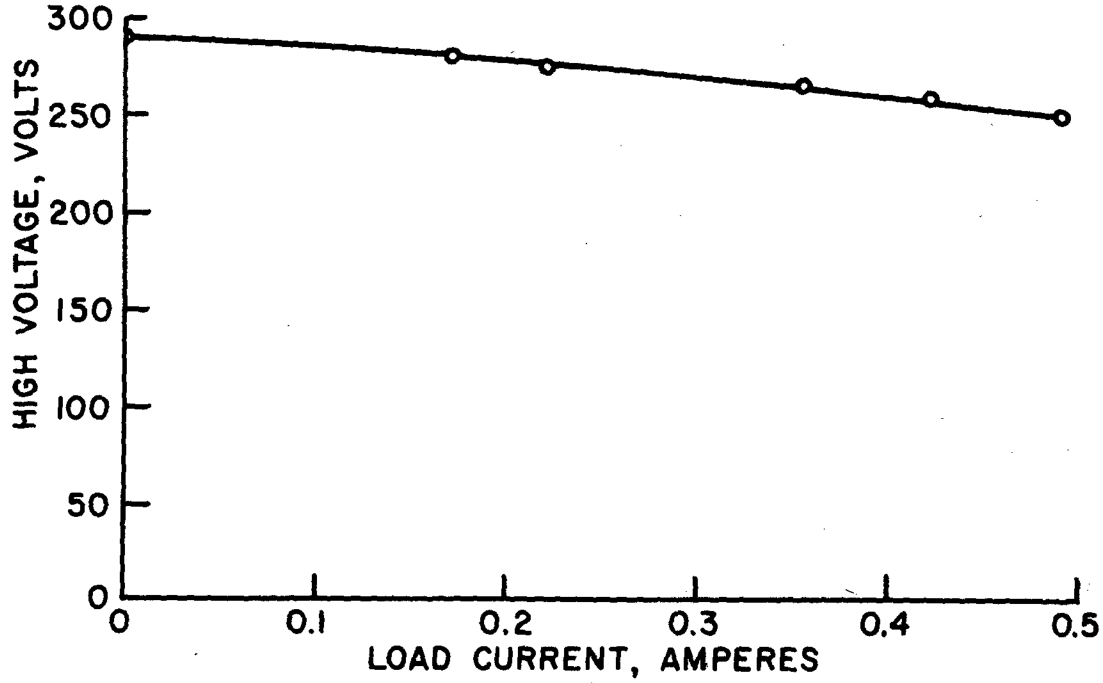

Figure 26. Output Voltages Versus Load Currents for the Permanent Magnet Generator Used for the Ruckstell-Hayward Power Supply for Radio Beacon AN/ART-27 (XA-1)

SECTION 3

RELIABILITY

3.1 INTRODUCTION

Earlier reports on this project, both progress reports and technical reports, have attempted to portray the potentialities and limitations of miniature engines, generators and components of engine-generator sets. The qualification of reliability has always been considered, and has been stated as a major limitation whenever promising performance characteristics have been presented for a given component or system. One of the primary functions of this project has been to gain experience with miniature equipment of this type and to determine something of its reliability. In earlier work when performance appeared promising, it was the practice to so report it, but to qualify future predictions of serviceability contingent upon development of the item to a satisfactory degree of reliability. Because of the general lack of previous effort with equipment in this size range, during the first two years of this project there was a tendency to be somewhat optimistic regarding the chances of ultimately achieving the desired reliability. However, the experience of the past two years on this project, along with recent experiences of others working with similar equipment, cast serious doubts as to how reliable some of these components can be made with present techniques.

In summary, it is the feeling of the authors that engine-generator sets which could be termed truly miniature can not be made reliable for military purposes in the near future. The nearest approach to such a miniature power source will probably be similar to what is predicted for engine weights in Figure 3.

In this day of rapid technological advancement, it would be extremely pessimistic to state that a certain degree of reliability could never be achieved for a piece of equipment such as a miniature engine-generator set. But to be practical, it is necessary at this point to look critically at each of the components of the subject power source and to ascertain their current state of reliability and the primary reasons for the failures which occur.

The reliability problems are associated primarily with the reciprocating engine and its component systems. The generator and associated electrical components, while they present some design problems, are essentially adaptable to miniaturization. With adequate development they would give good performance and reliability, even in extremely small and lightweight sizes. The inadequacy of the miniature reciprocating engine and its components suggests the advisability of investigating other types of prime movers if extremely small and reliable power sources are required.

3.2 LIMITATIONS OF COMMERCIAL DEVELOPMENT

When one compares the tremendous development effort which has been devoted to automotive and aircraft reciprocating engines over the past half century to the meager engineering effort which has been devoted to very small reciprocating engines, it is not surprising that the latter show poor promise at present from a reliability point of view. Even more revealing is the observation that with the larger engines many major problems regarding reliability and flexibility of operation have been solved by adding another component system to the engine. This always increases the size, weight, and complexity of the power plant. Thus, there are large spark plugs to increase the life of the plugs, elaborate and bulky ignition harness to prevent shorting or radio interference, a relatively heavy and large system for starting, a bulky heater for arctic climate starting, the complications of a supercharger for operation at higher altitudes, and a carburetion system which becomes exceedingly more complicated when it is required to meter fuel at any position of tilt, at various altitudes, and at extremes of temperatures. Many other features of modern automotive and aircraft engines could be cited which illustrate that considerable size, weight, and complexity have been added to these power sources over the years in order to solve particular problems of reliability or flexibility.

Only during the past few years has there been a commercial need for small or miniature power sources. The manufacturers of engines for model airplanes and boats had to meet the requirements of very light weight and low cost. The reliability problem was left to each consumer to solve in his own manner, which has never been done adequately. In fairness to these manufacturers, it must be stated that they build a surprisingly good product for the cost, and it meets its intended purpose quite well. However, it is not adequate for military purposes. Further, it appears that engines of this size and weight can not be developed into a satisfactory product for use in military engine-generator sets.

The many engines on the commercial market for use in power lawn-mowers, bicycles, chain saws, etc., have been classified earlier as small engines, as compared with the model airplane engines. They are also small but not miniature as compared to the size of engine visualized as needed for military miniature engine-generator sets. Again most of these engines have been designed and built with low competitive cost as a major design criterion. They serve reasonably well for their intended applications but tests have shown that many of them will not operate for more than 100 hours without major failures. (See reference 5). This is a satisfactory life for a lawn-mower engine, but inadequate for many military applications. Likewise the size and weight of these small engines far exceed a competitive position for a miniature power source, especially for short-term applications of a few hours. Also, these commercial small engines are designed and built to do a specific job under very normal conditions of engine operation. No provision is made for automatic starting, for exceedingly long periods of unattended operation, for operation at high altitudes, or for ease of starting in an extremely cold or hot environment. In short, this type of equipment has only a minimum of reliability and very little flexibility. To reduce the weight and size to that required for miniature engine-generator applications would require a completely new design and development program.

3.3 PROBLEMS CREATED BY MINIATURIZATION

Throughout this project, certain problems have become apparent which seem inherent with miniature equipment. Some types of apparatus are readily adaptable to construction in almost any size. In other equipment, like engines, new problems arise in the smaller sizes, some of which may be insurmountable or, at least, insoluble within the limits of reasonable time and development cost. The following sections of the report discuss some of these problems. Some recommendations are made as to the kind of solution which might be used to meet these shortcomings.

3.3.1 Fuel Metering System

The problem of metering the fuel uniformly and in the correct ratio of air to fuel is perhaps the most critical problem with miniature engines. A look at the quantities of fuel to be metered gives some insight into the complexity of the problem. Suppose a miniature two-cycle engine is to develop 0.25 hp (for a 100-watt power source) at 16,000 rpm with a bsfc of 1.5 lb per bhp-hr. The rate of fuel consumption is 0.375 lb of fuel per hour, or 0.0001 lb of fuel per second. To burn one pound of fuel, the engine would complete 2,560,000 cycles. Since the engine will operate satisfactorily within only a narrow range of air-fuel ratios, almost exactly the same quantity of fuel must be admitted to the cylinder each cycle. Hence, the one pound of fuel must be partitioned into 2,560,000 parts of almost exactly the same size. It is true that several cylindervolumes of fuel-air mixture would be contained in the crankcase at any given time, and this mixing volume would help level off minor fluctuations in flow rate. Still the engine is completing a cycle in about 0.004 sec, and it can not misfire for very many cycles without stopping. This requires that the flow rate be not only uniform, but that any minor fluctuations which occur must be corrected within a few thousandths of a second.

Another problem inherent with miniaturization of the fuel metering device is the size of constriction that must be used. To limit the flow of gasoline to the rate stated above, when a pressure differential as small as 10 inches of gasoline is created across an orifice, the drill size of the orifice must be 0.004 inches in diameter. This is smaller than the diameter of the holes in a diesel injection nozzle. Not only is this an extremely difficult machining job, but the possibility of dirt clogging the hole makes the chances for reliability rather low.

Admittedly, the example taken is on the low side of the fuel flow rates required for engines called for in the range of the contract, but it illustrates vividly the problem involved. For four-cycle engines running 6000 to 8000 rpm, at one bhp, the fuel metering problem is much less severe.

Difficult as this problem appears, it is believed that it can be met fairly satisfactorily with present designs of small carburetors for operation under environments normal to those of small engines. Thus, at air temperatures from 30°F to 100°F, with very little engine tilt, for manual starting, and attended operation, it is probable that a conventional design of carburetor, employing a float chamber, venturi, and main metering jet, with or without compensating jets, could be developed which would give a fair degree of reliability. No conventional carburetors were developed during the course of this project. However, some good designs are available commercially for the small, commercial engines. There seems to be no serious problem in adapting them to the miniature size. It should be noted at this point, however, that carburetor manufacturers point out that a rather lengthy development program is required to match a new design of carburetor to a given engine. This problem would be more involved and difficult in the miniature size range than it is for the present sizes of commercial small engines.

When great flexibility of application is required, including starting and operation at any degree of tilt, automatic starting, even in extremes of environment, etc., the carburetion problem becomes much more difficult. With present techniques it does not appear that a reliable fuel metering system can be made for this small an engine, to achieve such a degree of flexibility. The only metering principle that appears feasible is that of pressurizing the fuel tank and controlling the fuel flow rate with the use of constrictions. Various possibilities include varying the differential pressure across the constrictions, varying the area of the constriction, or both, to meter the fuel flow rate in response to the air flow rate. Any of these methods involve the use of extremely minute flow passages, with reliability problems much greater than encountered with the conventional carburetor. In injection-type aircraft carburetors, which provide for any degree of tilt, the fuel flow is metered through only one constriction, with a varying position vlave, even though the flow rate is astronomical as compared with that desired in a miniature engine. It is questionable whether such a fuel metering system for a miniature engine can be developed, because of the inherent problems associated with the minute flow areas. Attempts to develop such equipment on this project were not successful.

3.3.2 Ignition System

The ignition system is the second critical reliability problem with miniature engines. The glow plugs burn out within a few hours of operation. Once an engine is started, it may operate for an extended period of time with a burned-out plug; but when the engine is stopped, a new plug must be inserted before starting again. Both spark plugs and glow plugs, of the 1/4 to 3/8 inch thread sizes, tend to develop leaks between the center electrode and the insulation, reducing engine compression.

Again, there has been no commercial demand for very small spark plugs and glow plugs, except for the model engine market, where low first cost and minimum weight is of prime importance. It is possible that with additional development, very reliable miniature spark plugs would be available. The length of time before burn out in glow plugs could probably be increased considerably, if a concerted development program were devoted to it. However, one other serious problem is encountered which makes the feasibility of miniature plugs less likely, especially if long periods of operating time are desired.

There is a definite tendency for spark plugs and glow plugs to become fouled with deposits formed from the fuel and the lubricant. For periods of nearly continuous operation up to several hours, even miniature spark plugs of the 1/4-inch thread size might be made to serve satisfactorily, with suitable engine development. For longer periods of operation, one answer to plug fouling lies in using a larger plug. The Continental Motors Corporation, in developing the series of small engines for military use, is using an 18 mm plug to help eliminate the fouling problem (Reference 5). Other experience (Reference 8) with plug fouling in small two-cycle engines has indicated that the tendency may be reduced by using unleaded rather than leaded gasoline, by using nondetergent rather than detergent lubricants, or by using certain synthetic lubricants. Use of a higher heat range spark plug, higher cylinder temperatures, and larger spark plug gaps also reduced the fouling tendency.

When one considers again the comparison between aircraft engines and miniature engines, the tremendous demands expected of the miniature spark-ignition system is apparent. Actually the functions of the spark plug, breaker points, coil, ignition harness, and magneto for the miniature engine are almost exactly the same as they are for the aircraft engine which weighs several thousand pounds. In each engine the spark must ignite the mixture each cycle. The peak cylinder pressures which the plugs must seal are of the same order of magnitude. The average cylinder temperatures are of the same order of magnitude; in fact it would help the fouling problem if the miniature engine could run with higher spark plug temperatures. In a multi-cylinder radial bank, the breaker points have about the same number of cycles per minute as in a one cylinder miniature engine. The peak voltages required for ignition are approximately the same. Yet, the aircraft 18 mm spark plug weights 27 times as much as a 1/4-inch thread miniature plug. The differences in size and weight of the other ignition components are similar. If, after years of intensive aircraft engine development, it is considered necessary that the breaker points, coils, magnetos, and spark plugs for aircraft engines be as large and as heavy as they are to achieve reliability, it is not surprising that these same components are unreliable in very lightweight, miniature sizes. Undoubtedly, a development program aimed specifically at these components could make marked improvements in reliability over the present commercial components. However, in view of the experience with aircraft engines, it is doubtful if good reliability can ever be attained with components of the present miniature size. It appears to the authors that the only solution to reliability in the next several years involves the use of larger and heavier ignition components. At best, the weight and size of these components would lie somewhere between those for the present commercial model engine components and those for aircraft engines. Even the ignition systems for present commercial small engines are somewhat deficient from the standpoint of reliability.

3.3.3 Mechanical Design of Engines

As was pointed out in the first Technical Report of this project, Reference 1, the design and construction of the commercial model engines are satisfactory for their intended market but are completely unsatisfactory for military engine-generator application. While these engines have a specific weight of 0.6 to 1.4 lb per bhp, they are far too light to be reliable. In dynamometer tests it was found that the crankcases, which are often aluminum diecastings, sometimes will fail because of vibration and fatigue after a very few hours of operation. Crankshafts, connecting rods, pistons, and bearings also are subject to rapid failure, primarily because of the very lightweight design.

Each experimental engine designed and constructed by this project was made with a more durable crankcase, cylinder sleeve, and cylinder head. However, an attempt was made to keep the crankshaft, piston, and connecting rod comparable with the ones used in the model engines.

Service experience over the past three years indicates that good reliability cannot be obtained with miniature engines, where each part is designed to be very small and lightweight. In the case of the crankcases, cylinder sleeves, and cylinder heads, the experimental models which had greater rigidity gave no failures. Apparently the less durable model engines permitted deflections of the crankcase to such an extent that serious stress overloads were encountered. These deflections in turn lead to failure of other parts, such as connecting rods and crankshafts, owing to misalignments. Sleeve-type connecting-rod bearings were shown to have a short service life. Considerable wear in these bearings would invariably lead to failure of the connecting rod, probably because of the impact loadings which were caused by the large bearing clearances. Crankshafts were a component that gave considerable service troubles. Any misalignments caused by deflections or wear seem to cause severe stresses in the crankshafts. In addition, since the engine is a single cylinder one, severe torsional vibrations are encountered which require that the crankshaft be made larger and heavier than might seem necessary.

Design and construction of the valve gear for four-cycle engines is particularily difficult. The parts must be lightweight to reduce inertia forces, so that the valve gear does not float at high speed operation. The light parts in turn are subject to deflections which can cause misalignments and subsequent higher stresses. Either an L-head or an overhead valve mechanism can be built to operate with satisfactory reliability, but only at the penalty of some additional weight. Some failures of valves, excessive wear on cams, and breaking of valve springs have been encountered. Where larger and more rigid parts were used this type of failure did not occur.

Aluminum pistons which are only slightly thicker than those used in the better model airplane engines should give satisfactory service life for engine-generators. Much operating experience was obtained with Dooling pistons, even in the experimental engines, and they were found to be nearly adequate in their present design.

In contrast to the poor service life of sleeve bearings, antifriction bearings were found to be very satisfactory for these engines. A needle bearing for the connecting rod bearing (Figure 27) and ball bearings for the main bearings were found to give good service and trouble-free operation.

Figure 27. Typical Needle Bearing for Connecting Rod and Crank Pin

The problems of cylinder deposits and fouling can cause loss of power and ultimate stopping of the engine by plugging the exhaust ports or passages. The tendency for carbon deposits to accumulate in the exhaust passages is similar to that experienced with larger engines, with one exception.

In miniature engines the passages are much smaller, so that a relatively small amount of deposits will cut the flow area to half or one-third. As in larger engines, the deposits can be controlled partially by the proper choice of fuel and lubricant and by the operating conditions. For power sources needed for one-time applications, with operation of 24 hours or less, the deposits would be no serious problem. For longer periods of operation, they may contribute to service problems.

The air cooling system presents no unusual problems from a reliability standpoint, except that the small blower takes a relatively large percentage of engine power. For operation at higher altitudes, or in high temperature environments, the power requirement to drive the cooling air blower might take about half of the engine shaft power. It would be necessary to increase the engine and blower sizes for these applications, of course.

3.3.4 Generator

All tests on the developed dc, 120-volt, flat-compound, 12,000 rpm generators were made at ground level and at ambient temperature of about 25°C. Also, all exploratory tests on the flux-switch generator, the induction generator, and the permanent-magnet generator were made at ground level and at an ambient temperature of about 25°C. No altitude tests and no life tests have been performed on any of the generators. None of the generators has been tested for maximum safe speed and for maximum safe temperature. The bearing problem will be the same as that for the engines (precision bearings are recommended). Brush wear and commutator wear will be important factors in determining the life of the dc generators. Of course, the effects of high temperature and vibration on the insulation will be factors in determining the life of both the dc and ac generators.

In general, from observations of the generators under test conditions, the dc and ac generators should be fairly reliable for speeds less than 15,000 rpm, for altitudes less than 22,000 feet, and for total temperature of about 80°C.

3.4 PENALTIES OF FLEXIBILITY

The problems created by the necessity of designing for flexibility can be discussed here only in a general way. Since no satisfactory systems for achieving real flexibility with any small or miniature engines have yet been developed, it is impossible to cite specifically their effects on reliability. It has become an axiom of design, however, that the effort required to achieve reliability goes up with about the square of the number of components. Statistically, the over-all reliability of a system equals the product of the reliabilities of its n components.

$$P_{\text{over-all}} = p_1 \cdot p_2 \cdot p_3 \cdots p_n$$

Thus, reliability is not really an "ability," but the "probability" that a given piece of equipment will operate satisfactorily under service conditions. An engine-generator set which has 10 component parts, each having a reliability of 99 per cent would have an over-all power source reliability of 91 per cent. If the set has 50 parts having the same reliability, the over-all reliability would be only 60 per cent. If the component reliability of each of these 50 parts was 95 per cent, the over-all probability of successful operation would be 8 per cent.

If the engine-generator set is manually started and attended during operation, the probability of successful service would be much higher than if it is unattended, for two reasons. First, the person operating the set likely could correct some of the defects in functioning which might occur and thus increase the reliability of some of the less reliable components. Second, to attain unattended operation, the system itself must be much more complex with many more component parts. Many of these additional components employ new and untried design principles; hence the components themselves have lower reliability than some of the standard parts of a reciprocating engine or a generator. The same conclusion can be reached regarding a power source for operation at a very high altitude or in extremes of environment.

As was mentioned earlier, the engine and generator of the Ruckstell-Hayward power plant for use with Radio Beacon AN/ART-27(XA-1) were well designed and developed units. However, the reliability of the nitrogen pressure regulators was very low. The vane starting motor would seize on about 50 per cent of the starts. The hydrogen system for starting and warm-up was never made to function satisfactorily by the personnel of this project. The pressure regulators for the fuel system were very unreliable. In addition, the glow plug and the choke coil in the ignition system were of only nominal reliability. It is not surprising, then, that this power plant was never made to start automatically during the time it was available to this project. In contrast, the Ruckstell-Hayward Pockette power plant, employing the same engine and generator but depending upon manual starting and manual adjustment of the carburetor setting, gave quite good reliability and satisfactory performance.

Hence, while simplicity must be the objective of every good design, it cannot be attained in a system which requires great flexibility. Furthermore, it does not appear that good reliability can be built into special component systems, such as automatic starting systems, when these systems must be miniature in size and light in weight. At the present time it is impossible to state accurately the minimum weight and size of such systems that would be required to attain satisfactory reliability. It is the conclusion of the authors that the weight and size must be several times as great as the values listed in Table I for the Ruckstell-Hayward Radio Beacon power source.

SECTION 4

DESIRABLE DESIGN FEATURES

4.1 GENERAL

The preceding two sections of the report have indicated that there are considerable possibilities for miniature or small engine-generator sets, if they can be made reliable enough for the required service. This section of the report is intended as a summary of the experiences of this project, and related development projects, which point to desirable design features for such units. This discussion is not presented in great detail, as the reader is referred to the several references listed in the bibliography for more extensive information relating to design.

It is obvious that a project of this extent could not establish the optimum design parameters for all of the components listed in this section. Rather the experience gained to date is presented to enable one to visualize readily the general appearance of such equipment. It is hoped also that this section will prove to be a useful guide for designers in establishing the pertinent features of experiment models of engine-generator sets and their components. In each instance, a development program will be required to bring the equipment up to performance and reliability specifications. The extent of the development program will depend upon the amount of deviation from current designs of small engines and generators specified. A system which must be extremely light and compact will require a long and careful development program, if usual military reliability is required. If operation under extremes of environment is specified, the development period will be even longer.

4.2 ENGINE

The reciprocating engine for engine-generator sets of the size range discussed here should be a single cylinder design. At speeds of 6,000 to 12,000 rpm the piston displacement needed to develop about 2 horsepower or less makes the cylinder small enough using only one cylinder. The use of two or more cylinders wouldcomplicate the prime mover unnecessarily. With one cylinder, larger valves or ports can be used, a simpler valve mechanism or rotary valve arrangement is attainable, the number of engine parts is reduced, and many other simplifications result.

To study the desirable design features of miniature engines, nine engines were designed, built, and tested by project personnel during the period of this contract. These included three cross-scavenged two-cycle engines, one loop-scavenged two-cycle, one uniflow two-cycle, two overhead-valve four-cycle, one L-head four-cycle, and one compression ignition two-cycle engine. Each of the two-cycle engines could be operated with either glow or spark ignition. Many modifications to these engines were made to study the effects on performance of variables such as port timing, rotary valve timing, piston and cylinder-head shape, and compression ratio in these miniature sizes. All engines were 0.6 to 1.5 cu. in. displacement and operated at speeds greater than 5000 rpm. In addition to these experimental engines, the Ruckstell-Hayward Pockette engine-generator set (Reference 12) and the Ruckstell-Hayward Power Plant for Radio Beacon AN/ART-27 (XA-1) (Reference 13) were available for performance studies. Also many model engines were tested and a Spenco JB-2X two-cycle engine was borrowed for testing purposes from Mr. John Speaks of the Special Purpose Engine Co.

From experiences of this project, and of all who have worked with miniature equipment of this type, one axiom can be recommended strongly. The design must be simple. Unconventional and complicated miniature engines have been built which had so much friction that they would run at only a fraction of design speed even with no shaft load. It has been the disappointing experience of this project that the more complex designs of miniature engines are the ones which have frequent failures of the small and highly-loaded component parts. This does not imply that the engine must be a port-scavenged two-cycle design, but it does express definitely that a four-cycle design must be simple and clean-cut.

Principles of good mechanical design can not be abandoned just because the parts are miniature. It is intended that these prime movers are to be small power plants with high specific power outputs per pound and per size of equipment. As such, many of the parts are loaded more severely in the normal operation of these engines than in their larger size, commercial counterparts.

4.2.1 Cycles and Ignition Method

The four-cycle spark-ignition engine appears to be the superior prime mover for miniature and very small engine-generator sets. In this study it was found that the four-cycle design was more reliable, started more easily, was capable of operating at higher altitudes, was less sensitive to minor fluctuations of the fuel metering system, and gave much better specific fuel consumption than the two-cycle engines designed and tested. Performance at part load and at idling are also much better for the four-cycle engine. There is some penalty in weight and engine size of the four-cycle over the two-cycle design, but if reliability is of high importance, the four-cycle design has a much better chance of yielding a satisfactory power source. The four-cycle design may be L-head or valve-in-head. The breathing characteristics of the latter design are definitely better, but the simplicity of the L-head (Figures 28 and 29) valve mechanism is attractive and permits good reliability.

Experience with the military small-engine program, Reference 5, has shown that the four-cycle engines of approximately eight cubic inches displacement showed definite superiority over the two-cycle engines of the same power output. For the military series of small engines, the four-cycle design has been selected for all engines of 1/2 hp through 20 hp.

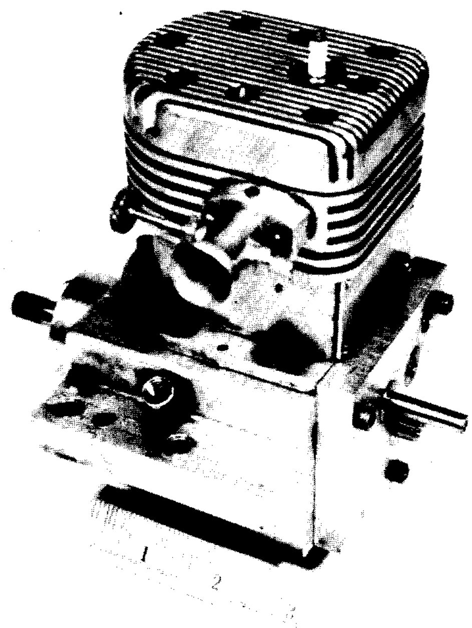

Figure 28. L-Head, Four-Cycle Engine

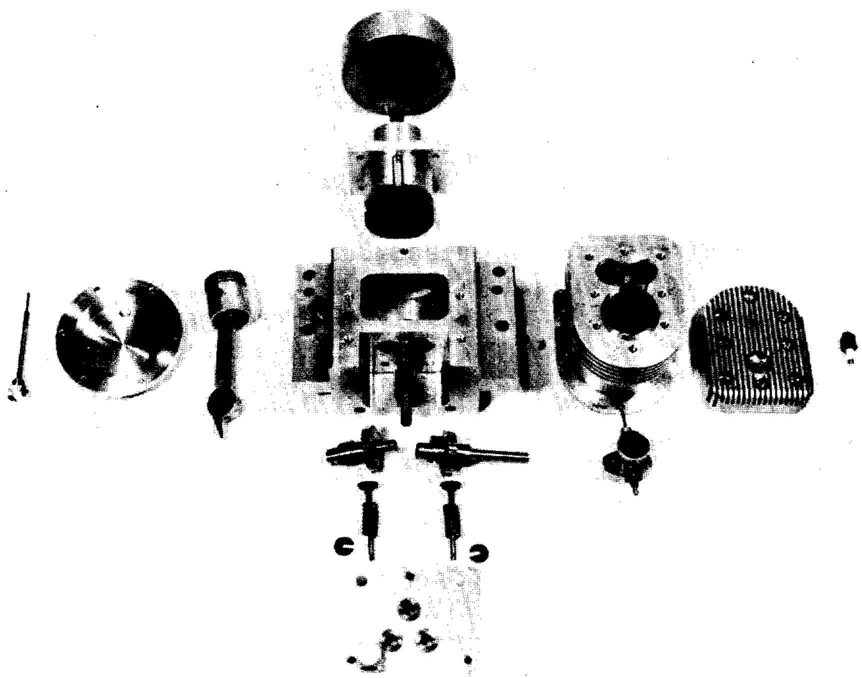

Figure 29. Disassembled View of L-Head, Four-Cycle Engine

Comparative tests showed that the two-cycle engines of 1-1/2 hp rating were deficient in the following respects as compared with the target values of desired characteristics: compactness, long life, ease of starting, quietness, servicing intervals, and sustained power. Four-cycle engines of the same rating were slightly short of the target values on some of these characteristics, but were better than the two-cycle engines. Less extensive test experience on this project shows the miniature four-cycle engines of 1/2 to 1 hp capacity are better than the two-cycle ones for the same reasons.

In miniature sizes the two-cycle engine could be built a little more compact and somewhat lighter than a four-cycle type. For operating periods of about 5 to 10 hours, the weight saving of the two-cycle design might be enough to warrant the development program necessary to overcome some of its chief shortcomings, as indicated in Fig. 6. For greater lengths of operating time, the inherently lower fuel consumption of the four-cycle engine would offset the initial difference in engine weights.

The two-cycle engines using either loop-scavenging or cross-scavenging have been shown to be satisfactory. Both types have been operated with about 1.5 lb fuel per hp-hr as the minimum brake specific fuel consumption. Both types produce about the same power per cubic inch of displacement. There is little advantage in the one type over the other. The cross-scavenged type will often give slightly better BSFC.

A two-cycle uniflow engine, with crankcase compression and transfer ports for inlet and an overhead valve for exhaust, did not give good performance in this size of engine. Attempts to use an exhaust butterfly valve to close the exhaust passage prior to the closing of the inlet ports likewise did not prove satisfactory. Another manufacturer found that a miniature opposed-piston engine was completely unsatisfactory. All of these experiences emphasize the fact that the mechanical design must be as simple as possible and more or less along conventional lines.

Glow ignition has been found to be relatively satisfactory for two-cycle engines, but completely unsatisfactory for four-cycle units. Even with the two-cycle engines, better power and better fuel consumption were obtained with spark ignition. Moreover, the reliability of the components of a spark-ignition system is better than for the glow plug and batteries. If the engine is required to start and stop several times, the glow plug is not satisfactory as it may burn out after one or two starts and subsequently fail to start the engine.

If a two-cycle engine were selected for a very lightweight power source for a one-shot application, requiring only a few hours of operation, glow ignition might be preferable to spark ignition because of the slightly lighter weight ignition system required.

Miniature compression-ignition two-cycle engines are very sensitive to proper adjustments, and thus are so unpredictable in performance that they are not considered satisfactory for these applications. A fuel injection system for these sizes is completely unrealistic.

4.2.2 Design Speed

The design speed should be chosen to suit the generator design and the electrical requirements. Experience with this project shows that there are no serious objections to design speeds as high as 12,000 rpm for two-cycle engines and as high as 8,000 to 10,000 rpm for four-cycle engines. One experimental L-head engine designed for 8000 rpm has given very satisfactory performance and no signs of early failure at speeds as high as 11,500 rpm. Noise level is much higher at these speeds than it is for engines operating at 3600 rpm, of course, but the increased power output per cubic inch of displacement warrants the use of the higher speeds when weight reduction is essential. So long as reasonable piston rubbing velocities, proper engine balancing, and a good choice of bearings are incorporated into the design, the high operating speeds are acceptable. At speeds higher than those recommended above, operation is frequently unpredictable and sensitive to many operating variables. This unstable condition at higher speeds is caused principally by the greater frictional drag of inducting the charge and exhausting the gases, by more stringent fuel-metering requirements, and by greater engine friction.

4.2.3 Cylinder Dimensions

The factors influencing the choice of bore and stroke dimensions, bore/stroke ratio, connection rod length/crank throw ratio, compression ratio, port timing, and clearances are discussed rather extensively in Part II of this series of Technical Reports, Reference 2. Pages 18 through 37 of that report present design charts and data and a design procedure for arriving at the basic cylinder dimensions. Experience of the past one and one-half years of this project as well as recent reports on other small engines indicate that no appreciable changes in that information are warranted. Hence, this information will not be reproduced here. Recent test results serve to substantiate that the orders of magnitude of BMEP values reported in Reference 2 are correct. No significant improvements of this type have been made by this project or other small engine development projects in the past two years.

As in any engine design, many factors must be considered in arriving at the compromises necessary to establish the principal design features of a miniature engine. Once such factors as provision for overload, length of service, type of service, reliability, length of development time allowed, operating environment, etc. have been duly considered, the design data presented in the previously mentioned report can be used as a guide for choosing the basic dimensions of the experimental model.

The compression ratio should be between 7 and 9 to 1, based on full piston displacement, for both 2- and 4-cycle engines. In contrast with larger engines, miniature engines have an optimum compression ratio. At higher compression ratios there is a decrease in power and economy, probably because of a quenching effect resulting from the very small clearance between the head and the piston.

Basic dimensions of an engine which should be suitable for many types of applications for a miniature engine-generator set rated at 200 watts might be as follows:

> Four cycle, spark ignition, 8000 rpm, 0.8 bhp, 1.25 inch bore, 1.05 inch stroke, 1.29 cubic inches displacement, 62 bmep, 7 to 1 compression ratio; 1400 ft. per min. mean piston speed, 0.62 hp per cu in.

These values are given here only to establish the typical dimensions which might be used for a miniature engine for these purposes.

4.2.4 Connecting Rod, Crankshaft, and Piston

These components are highly stressed in a high output miniature engine and must be designed with the same care and allowance for unusual loading as with larger commercial engines. Although the forces involved are relatively small for machine parts, the parts themselves are small, so that stresses and deflections may be quite large. Excessive deflections may cause serious misalignments, resulting in failure of one of these components or of the crankcase. The same careful consideration for avoiding stress raisers and allowing for vibration-induced stresses must be devoted to the design of these components as for any highly loaded machine element. With a proper design and a reasonable development program, there is no reason why these components could not be as satisfactory for miniature engines as they have become in larger engines. This also implies that adequate weight and size of these components is necessary to retain reliability.

The experience with the project experimental engines has shown that these components must be larger and heavier than the same components used in model airplane engines. The crankshaft must be a high strength steel. It would be preferable if the crankshaft and generator shaft were integral. This design would increase rigidity and would eliminate the complication of a coupling, which is a likely source of failure in a small shaft. A check was made to determine whether the natural torsional frequency of the crankshaft-generator shaft lay within the range of operating speeds of the engine. The vibrating system was assumed to consist of the armature of the generator and the equivalent inertia of the crank throw, connecting rod and piston, connected by a solid steel shaft as shown in Figure 30.

The natural frequency of such a system is given by the formula

$$f = \frac{1}{2\pi}\sqrt{\frac{(I_1 + I_2)GgI_p}{I_1 I_2 L}} \tag{1}$$

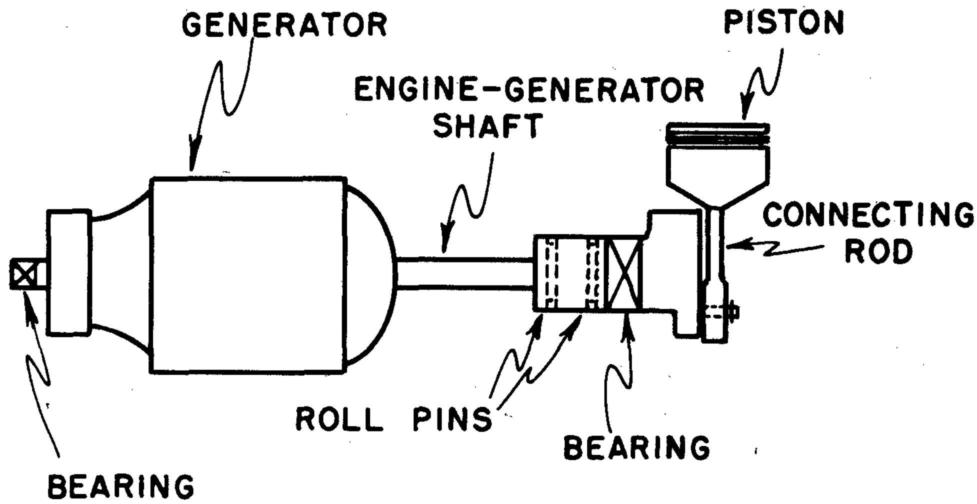

Figure 30. Diagramatic Sketch of Engine-Generator Assembly

where

f = natural frequency, cycles/sec.
I_1, I_2 = moments of inertia of masses about axis of shaft, lb-in.^{2}
G = shear modulus of elasticity of shaft material, psi.
g = gravitational constant = 386 in/sec.^{2}
I_p = polar moment of inertia of circular cross section of shaft, in.^{4}
L = distance between masses, in.

The inertia I_1 of the armature was estimated to be 0.283 lb-in^2 and the equivalent inertia I_2 at the engine end to be 0.0612 lb-in^2. The shear modulus of steel is 11,500,000 psi. The polar moment of inertia I_p of a circular shaft is $\pi D^4/32$.

Substituting these values into Equation (1) and simplifying gives:

$$f = 14,800\sqrt{\frac{D^4}{L}} \qquad (2)$$

In order to evaluate the effect of changes in the diameter D and length L of the shaft, the following calculations were made with Equation 2. First, assuming a representative distance L between masses to be 2.3", a plot was made of the variation of natural frequency with diameter. Second, assuming the maximum operating speed to be 8,000 rpm, a frequency of 133 cps was substituted into Equation (2) and a plot of the length of shaft required to yield a natural frequency of 8,000 cpm was made vs. shaft diameter. These curves are shown in Figures 31 and 32 respectively by the solid lines.

If a larger generator were to be used, the natural frequency of the system would be reduced still further and it was thought advisable to determine the vibration characteristics of a configuration utilizing the heaviest possible generator. Since the inertia of the generator is already much larger than that of the engine parts, it was assumed for this calculation that $I_1 \gg I_2$. Therefore $I_1 + I_2 \cong I_1$ and Equation (1) becomes

$$f_{\infty} = \frac{1}{2\pi}\sqrt{\frac{GgI_p}{I_2 L}} \qquad (3)$$

where f_{∞} is the natural frequency corresponding to a very large generator, and the other quantities are as previously defined. Substituting these values into Equation (3) gives

$$f_{\infty} = 13,420\sqrt{\frac{D^4}{L}} \qquad (4)$$

Plots similar to the solid lines in Figures 2 and 3 were made of f_{∞} vs. D for L = 2.3" and L vs. D for f_{∞} = 133 cps. These are shown by the dotted lines in Figures 31 and 32.

Figure 31 shows that the natural frequency of the proposed system will be greater than twice the operating speed if the shaft diameter is larger than 3/16". Figure 32 demonstrates that the natural frequency will approach the maximum operating speed only if the shaft is exceedingly long or has a very small diameter. Therefore it was concluded that the torsional oscillations of this system will not present a severe problem for the designer.

The connecting rod may be made of aluminum alloy, titanium, or steel. In any of these materials, care must be taken to avoid stress raisers. For that reason, a one-piece connecting rod with no bearing cap is preferable. The crankshaft can be made with an overhung design, or be assembled from two members and fastened securely, with greater chance of attaining reliability than by using a two-piece connecting rod.

The piston may be an aluminum die casting. The pistons manufactured by the Dooling Co. (Figure 33) for the Dooling 61 model aircraft engines were found to be nearly adequate in their present state of design. An increase in wall thickness of about 30 per cent in that particular piston should eliminate the few failures which were experienced. In two-cycle

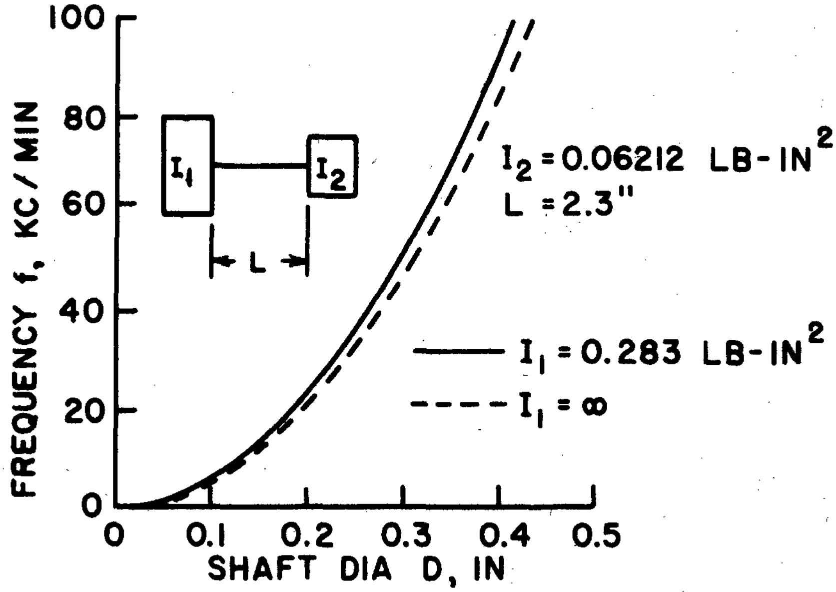

Figure 31. Natural Frequency of System with Shaft Length of 2.3" vs. Shaft Diameter

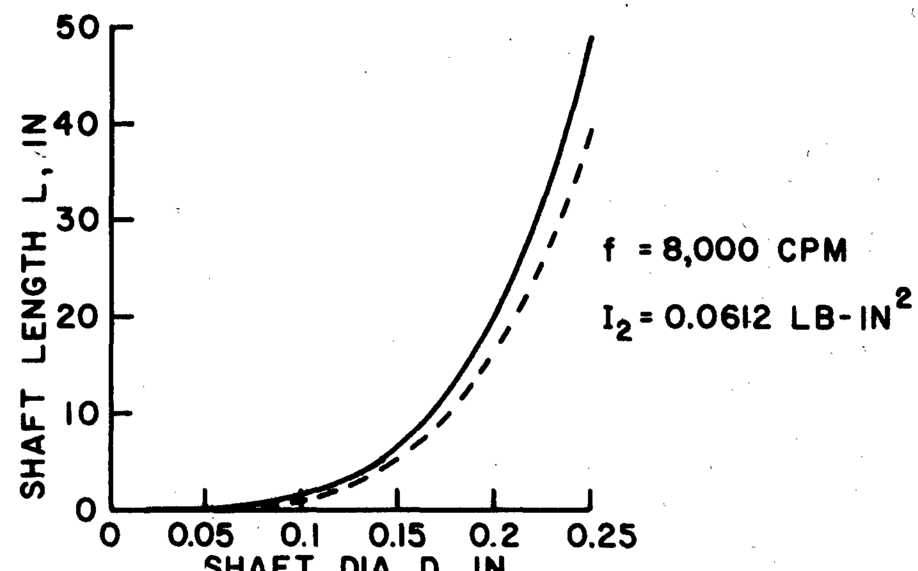

Figure 32. Shaft Length Required to Give Natural Frequency of 8,000 cpm vs. Shaft Diameter

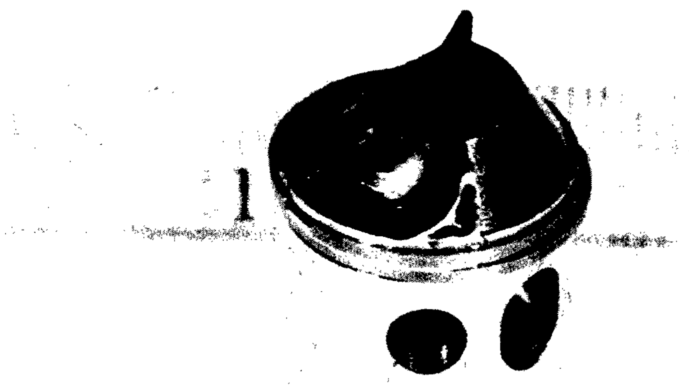

Figure 33. Dooling 61 Piston

cross-scavenged engines, there seems to be some advantage in using a smoothly shaped deflector on the piston head to aid in efficient scavenging. In other engines, the simple flat-head piston is probably the best type. For any engine design, the use of cast iron piston rings gives the best results. Two compression rings located above the piston pin appear to give adequate service, although no long-term oil consumption tests have been conducted on miniature four-cycle engines using splash lubrication in the oil sump. The addition of an oil-control ring might be beneficial with this type of engine for long periods of continued service.

4.2.5 Four-Cycle Valve Mechanism

Although miniature in size, the various components of the valve mechanism go through extremely high accelerations and decelerations when operating at these engine speeds. Thus, good standard practice in the design and manufacturing of the cam, valve springs, valves, and rocker arms is required.

A careful compromise is necessary between the desire for light weight to reduce inertia forces and the need for greater stiffness to avoid excessive deflections. If good design practice is followed, using materials conventionally used for high-output, larger engines for the valves, valve guides, valve-seat inserts, valve springs, and cams, a reliable valve mechanism can be made to operate satisfactorily at speeds up to 10,000 rpm or higher.

Both overhead valve and L-head designs have been used with reasonable success in experimental engines. With both types adequate cross-sectional flow area must be provided throughout the inlet passage to get good volumetric efficiency. The overhead valve arrangement is slightly preferable because of the better engine breathing and reduced combustion chamber surface attainable, but the L-head design offers a small reduction in mass of the valve mechanism. The simplicity of the latter helps in meeting the manufacturing tolerances required, also. With either design, the camshaft should be located in the crankcase and gear driven from the crankshaft. Experience has shown that overhead camshafts, driven through a chain and sprocket mechanism, introduce many serious problems. At these speeds and sizes the chains loosen, the sprockets wear excessively, the mechanism is difficult to keep in alignment, and the timing does not remain fixed.

4.2.6 Two-Cycle Induction System

The two-port type of design using crankcase compression is the only two-cycle design which appears feasible for miniature engines. In general, it is felt that the timed crankcase rotary valve will yield engine performance superior to that afforded by the pressure-actuated, or reed, valve for constant engine speed application. When idling or variable speeds are required, the reed valve may be the better. In miniature engines at high speed operation, there is some problem in obtaining a reed valve design which has a low enough mass in the vibrating reed to yield good volumetric efficiency. With rotary valves, the critical problem is that of obtaining a good seal when the valve is in the closed position and yet keep face friction within permissible limits. Timing of the crankcase rotary valve depends upon engine speed. Typical values show the dwell time to be from 150 to 200 degrees, with closing at 30 to 70 degrees after top center.

As stated in 4.2.1 above, either cross-scavenging or loop-scavenging may be used. Other types of two-cycle design do not seem to yield good performance in miniature power plants. Transfer ports should allow flow directly from the crankcase to the cylinder, without requiring flow through the piston skirt as an additional constriction in the flow path. Studies of port timing for a 14,000 rpm cross-scavenged engine show that the exhaust port should be opened about 72 degrees and the inlet port at 60 degrees before bottom center. Both values are based on the time at which the piston crown uncovers the port.

Contrary to statements made in earlier reports by this project, more recent experience indicates that crankcase compression is not significant in determining engine performance (see Section 5, Reference 4). In this study, arrangement was made to vary the crankcase compression ratio of a cross-scavenged engine from 1.11 to 1.31 while the engine was in operation. No significant variations in speed or power output were noted throughout this change.

4.2.7 Bearings

At the high speeds required for this service, the antifriction bearings have been found to be much superior to sleeve bearings. Either ball or tapered roller bearings for the main bearings give excellent service, even though the speeds are often considerably above the catalog ratings. For this reason, a precision quality of bearing is preferred. Sleeve bearings will serve satisfactorily for the main bearings if the bearings loads and speeds are kept very conservative.

The "independent roller," or needle bearing, as used in the Dooling 61 model engine, is the only connecting rod bearing which has given good service in the experimental program of this project. This particular bearing uses a hardened crankpin of 0.259 in. diameter as the inner race, rollers of 0.063 in. diameter and 0.250 in. long, with a hardened steel outer race having an i.d. of 0.387 inch. The outer race should be of one-piece design, which again requires an overhung or an assembled crankshaft. A two-piece outer race does not give as good a life, because of the ragged joint between the halves which is almost certain to appear in this small size. Bronze sleeve bearings are completely inadequate for connecting rod bearings at these speeds, even when generously sized.

Plain bearings are used for piston pin bearings in all types of small and model engines. They give satisfactory service if properly sized and fitted.

4.2.8 Crankcase, Cylinder, and Head

The crankcase may be lightweight, but it must be rigid enough to prevent excessive deflections. Aluminum or magnesium castings are adequate. A welded steel construction also would give good strength and rigidity with reasonably light weight.

The cylinder may be an aluminum casting, or it may be machined from an aluminum block, with the fin spacings machined. Good, lightweight cylinder construction also has been achieved by welding steel fins to a steel sleeve. This gives an integral design, whereas with the aluminum cylinder a hardened steel sleeve must be used. Cooling seems to be adequate with either the aluminum or the steel fins.

The same material options exist for the cylinder head. A small dome in the cylinder head, approximating a hemispherical combustion chamber, probably gives the best performance. If overhead valve design is used, the valves may be tilted at an angle to conform with one side of the dome. In two-cycle cross-scavenged design, the cylinder head must take the contour of the piston head to keep the compression ratio high enough. Experience shows that the spark plug should be located in miniature engines by the same principles as are applicable to the larger ones -- either in the middle of the combustion chamber, or else slightly closer to the exhaust valve, depending on the type of engine design employed.

One of the problems frequently encountered with very small engines is that of securing the cylinder head firmly to the cylinder. The threads in the aluminum cylinders are not very strong in these small sizes, and there is room for only a few machine screws. The use of steel bushings in the cylinder helps to solve this problem. One manufacturer solves it by using an integral cylinder and head. The Ruckstell-Hayward Company utilized a welded construction (Figure 34).

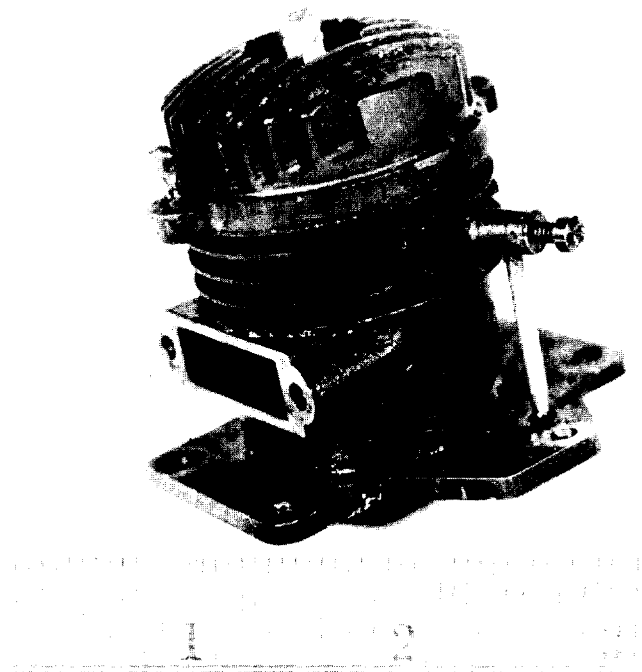

Figure 34. Welded Construction Used on Ruckstell-Hayward Cylinder

4.3 GENERATOR

No attempt will be made to discuss the advantages of the different generators under different operating conditions. Only a few desirable features will be given.

(a) DC Generators. - The voltage regulation curve of a dc compound-wound generator can be adjusted more easily than that of a dc permanent magnet generator. Satisfactory operation may be obtained with two main poles and no interpoles. The short-shunt connection is suggested although there is not too much difference between this connection and the long-shunt connection.

(b) Flux-Switch Generator. - The flux-switch generator may be considered as a machine which falls in the general class of high-frequency inductor alternators. The armature flux linkage of the flux-switch generator varies between equal positive and negative magnitudes in contrast to the pulsating unidirectional flux change which takes place in the more conventional inductor alternator. This difference in armature flux changes may give an advantage to the flux-switch generator over the inductor generator from the standpoint of power output and losses. It should be noted that the flux-switch generator may have either permanent magnets or field windings for approximately the same basic performance.

(c) Inductor Generator. - The inductor generator may have field excitation or permanent magnets for setting up the necessary flux. The waveform is nearly sinusoidal. It may have a weight advantage but this needs to be investigated.

(d) Induction Generator. - An induction generator, plus its necessary capacitors for excitation and additional capacitors for improving voltage regulation, may be only slightly heavier than a permanent-magnet generator. Its waveform is satisfactory. This type of generator has the advantage of not depending on an external voltage source as long as it does not lose its residual magnetism. It appears to be a good idea to bring the generator to rest with the load disconnected and the capacitors connected so that sufficient residual magnetism will remain.

(e) Permanent-Magnet Generator. - The permanent-magnet generator is very reliable as an emergency power supply since the permanent magnets are satisfactory and it does not depend on external dc supply for field excitation. Voltage regulation may be improved by combining permanent magnets and regulating devices.

(f) Conventional Synchronous Generator. - Conventional synchronous generators usually have good waveform and good voltage regulation, although they require dc supply for field excitation. Its weight may not be too bad when compared with a permanent-magnet generator and its regulating devices.

4.4 FUELS AND LUBRICANTS

4.4.1 Fuels

Miniature engines have essentially the same fuel requirements as small commercial engines. Gasoline of about 80 octane number gives good performance. Antiknock qualities of the fuel have little influence on performance, regardless of the type of engine. Detonation is seldom found in the normal operation of miniature engines, so that very low antiknock gasolines may be used with no sacrifice in performance. Values of BMEP and BSFC are almost identical, regardless of the octane rating of the fuel used.

Experiences of other investigators, References 7, 8, indicate that small commercial engines have longer periods between overhauls if low octane fuels, with little or no tetraethyl lead content, are burned as compared to more highly leaded, high octane fuels. No long periods of continuous operation have been accumulated with the miniature, high speed experimental engines on this project. From the experience gained, however, it appears that the deposit problem is similar to that for the small commercial engines. Thus, the rate of buildup of carbon deposits in the exhaust ports of two-cycle engines, the fouling of spark plugs with carbon and lead deposits, and the buildup of lead and carbon deposits on the piston head, cylinder head, and exhaust valve, are similar to the problems of this type which occur with larger engines. A fuel with greater volatility reduces the tendency for deposits to form. It has been found that kerosene can be made to yield values of BMEP and BSFC almost as good as those for 80 octane gasoline. The kerosene shows a greater tendency for deposit formation and increases the starting problem, however.

Tests with propane indicate that a liquefied petroleum gas, LPG, may be a very desirable fuel for a miniature engine-generator set, especially if operation for only several hours is required. For longer periods of operation, the weight of the storage tank becomes excessive. Since the starting characteristics for LPG are definitely much improved over those for gasoline, kerosene, or alcohol, it should certainly be considered as a potential fuel, particularly if starting at very cold temperatures is required. LPG is especially promising for engines for 200 watts power source or less since the fuel system is already pressurized and the carburetor would meter a gaseous flow rather than a liquid. It is suggested that the specifications for the LPG fuel could vary the percentages of propane, butane, and pentane permitted to yield a mixture which has a sufficiently high volatility to obtain the starting characteristics in cold climates needed, and yet maintain the vapor pressure low enough to keep the storage tank from being excessively heavy. For engine-generator sets designed for a particular application, this could be accomplished. It would probably not be satisfactory for a general purpose power source intended for great flexibility of applications.

Alcohol-base fuels do not offer any advantage over petroleum fuels for miniature engine-generator applications. The alcohol fuels permit slightly higher power per cubic inch of displacement, probably because of the lower inlet mixture temperatures resulting upon evaporation of the fuel. This small increase in power is essential for model airplane racing, but is insignificant for engine-generator considerations. Starting tests indicate that higher starting speeds are required with alcohol fuels as compared with gasoline, again probably because of the greater heat of vaporization of the alcohol. In addition, the BSFC values for alcohol-base fuels are three to five times those for gasoline.

Tests with various power augmentation additives show little improvement in engine performance. Nitromethane, nitropropane and amyl nitrate were added to methanol-base fuels in various percentages and the mixtures tested in miniature engines. A modest improvement in bhp was obtained, generally because the engine would develop about the same BMEP, but would peak at a higher speed. Values of BSFC and starting ease were unchanged. This experience agrees essentially with that reported in Reference 9, where performance with various mixtures of nitromethane in methanol, gasoline and benzene were reported. With more accurate measurements of power, conducted with larger size engines, it was found that 20 per cent nitromethane in methanol increased the power output 12.7 per cent over that with methanol alone. The BSFC was essentially unchanged from that for methanol. With benzene, even smaller increases in power output were obtained. With miniature engines, the problem is not so much one of pushing the engine displacement to a maximum power output, but rather one of obtaining starting ease, reliability, and good efficiency with what inherently is a prime mover with high specific power output.

4.4.2 Lubricants

There is no simple or general conclusion regarding the best lubricant for miniature engines. With miniature engines, as with all other engines of any size, the variations in performance with different types of engine design is much greater than the variations in any one engine caused by using different lubricants. Most experience on this project involved the use of mildly detergent, petroleum base oils. No particular problems were encountered, although most of the experience was with tests of relatively short duration. Six to ten per cent by volume of SAE No. 70 oil in gasoline was used for two-cycle engines. SAE No. 20 oil was used in the crankcase sump for the four-cycle engines. No appreciable wear chargeable to poor lubrication was noted. Engine deposits were not excessive. Much experience with the small commercial engines shows that lower viscosity oils leave fewer combustion chamber and exhaust port deposits. The thinner mixtures of oil in the gasoline also leave fewer deposits in the two-cycle engines, but about one part of oil to 16 to 20 parts of gasoline is the thinnest mixture which will give adequate lubrication for a high-output engine.

Castor oil may give slightly better lubrication than petroleum oils in two-cycle engines. The friction horsepower has been observed to be slightly lower with castor oil. However, it also forms gummy deposits in the cylinder and exhaust passages. In view of the fact that it will not mix with gasoline without the use of an emulsifier, it is not recommended that castor oil be used as the lubricant. Various synthetic lubricants appeared to give adequate service, but no marked improvements were noted with them in the rather limited tests of this type which were conducted. For operation at extremes of environments, it is likely that one of the new synthetic lubricants would be very beneficial.

4.4.3 Lubrication Systems

Unusual types of lubrication systems do not seem to be warranted or even desirable for miniature engines. With two-cycle engines, crankcase lubrication with a fuel-lubricant mixture is adequate. Four-cycle engines can be lubricated with splash lubrication from a crankcase sump. In the L-head design even the valve mechanism may be lubricated adequately in this way. With proper crankcase design, splash lubrication could be used, even when the engine might be subject to a wide variation of tilt. If operation in completely inverted positions were required, then another type of lubricating system would be necessary.

One four-cycle experimental engine designed and built by this project utilized a pressurized lubrication system. A small gear pump of conventional type design was used. It was found that such a system would provide ample oil circulation, but that it complicated the design and construction considerably. For that reason forced lubrication is not recommended unless completely inverted operation is a requirement.

Some attempts have been made to lubricate two-cycle engines by admitting the oil separate from the fuel. No very satisfactory techniques of this type have been developed. The oil consumption required for adequate lubrication is much greater than when the oil is mixed with the fuel. Also the oil metering problem is even more difficult than the fuel metering problem, since much less oil flow is desired. For this reason, the use of LPG for fuel would probably be most advantageous in a four-cycle engine, rather than in a two-cycle design with a separate lubrication system.

4.5 CARBURETION

The fuel metering system will require the greatest development effort in any new design and development program for a miniature engine. At the present time no satisfactory designs are available, either commercially or in the experimental stage.

For usual types of service, with manual starting and attended operation, with operation at nearly level position in normal environmental conditions, the conventional type of small engine carburetor should be satisfactory. The smaller the engine size, assuming good fuel consumption, the greater the development effort which will be required to adapt present design principles to this size of carburetor.

Operation under more demanding conditions will require a pressurized fuel system with a unique design of fuel-metering element. The pressure regulators necessary for this type of system also will require some ingenious design to give good reliability with the minute flow rates involved. Contrary to earlier opinions on this subject, the evaporation problem does not seem to be very critical for miniature engines. Early in the project it was believed that the most critical carburetion problem was that of evaporating the fuel in the manifold or in the crankcase. Tests with fuels of varying degrees of volatility showed that evaporation apparently is essentially complete even for fuels like kerosene. Various pure hydrocarbons with boiling points from $-44^{o}F$ through $210^{o}F$ gave practically the same power outputs and fuel consumptions. Thus, it was concluded that for laboratory conditions the fuel must be nearly evaporated by the time it is ready to burn in the cylinder, since the volatility of the various fuels had so little effect on performance. This was true with a four-cycle engine and with two different two-cycle engines. It was also concluded that various devices to aid evaporation, such as manifold hot spots, long manifolds, a great deal of turbulence in the manifold or crankcase, etc., were of little value, except perhaps for aid in starting.

The real problem then is to provide an extremely small but uniform fuel flow rate, in response to a measured air flow rate. Some suggestions for achieving this which have been considered by this project are discussed here.

Fuel flow may be regulated by the unique method of variable flow resistance. As the length of the flow passage is increased, the flow velocity, and hence the flow rate, is decreased. Some success in producing a uniform flow rate was achieved with a device utilizing the principle of variable flow resistance. The major components of the device, called a spiralflow regulator were a plunger, a cylinder and a means of adjusting the position of the plunger in the cylinder. A "V" shaped groove was cut in a spiral fashion around the plunger forming the flow passage for the fuel. The fuel entered at a fixed location on the side of the cylinder, flowed through the "V" groove and emerged through an axial hole in the plunger. The flow rate was varied by exposing more or less of the "V" groove to the fuel. Because air seeped into the fuel line, the original model was redesigned with the plunger integral with a pressurized fuel tank. The air leakage problem was eliminated but friction due to the "O" ring seals remained at a high level. Friction is a detriment in that some difficulty was experienced when making quick adjustments of the plunger position. A reduction of frictional forces is necessary if a future design, utilizing the flow resistance method of flow regulation in conjunction with a mechanical or air operated governor, is to perform satisfactorily.

Regulation of the fuel flow may be achieved by variation of the pressure difference between the inlet and outlet of a fuel nozzle. The result is a proportionate change in the fuel flow rate. An experimental carburetor employing this method consisted of a venturi, a moveable fuel nozzle concentric with the venturi, a mechanism to vary the nozzle position in the venturi and a needle valve for initial adjustment of the fuel flow rate.

Once the needle valve adjustment has been made, the flow rate is regulated by varying the position of the nozzle in the convergent section of the venturi. Future designs utilizing this principle may incorporate a mechanical governor or diaphragm mechanism to vary the nozzle position in response to engine demands.

The most feasible means of fuel regulation seems to be a pressurized fuel system employing a pressurized fuel tank, a pressure regulator, a constriction, an air-bleed mechanism and a venturi. The pressure regulator maintains a constant pressure at the orifice, and the flow rate may be regulated by adjusting the amount of air-bleed downstream of the constriction. The resulting bleed-air and fuel mixture flows through the nozzle into the venturi where it is mixed with the main combustion air. The possibility of using the flow resistance method instead of an orifice or a constriction to meter the fuel flow rate seems promising, but as stated above certain difficulties in a fuel regulator of this design must be surmounted to achieve the desired degree of reliability.

A metering device used to regulate a gaseous fuel such as propane will have a higher degree of reliability than one used to regulate a liquid fuel because the flow passages are larger. Commercial propane was supplied from a primary pressure regulator and tank to a secondary pressure regulator and venturi. The gas pressure at the orifice in the venturi throat was varied by adjusting the spring tension on the diaphragm of the secondary pressure regulator. If the throat pressure decreased the diaphragm moved in such a manner as to open a tire-type valve allowing an increase in gas flow. Ease of starting and flow regulation were achieved, but the low power observed was probably due to improper matching of the venturi size to the engine.

4.6 IGNITION SYSTEM

For almost any application of miniature engine-generator set, a spark ignition system with magneto would be the optimum type of system. It is true that use of a magneto would increase the weight and size over what could be attained with some other types of systems, but over-all reliability and flexibility make it appear desirable. To achieve reliability, it will be necessary to keep the design closer to that now being used for small commercial engines than to that sometimes used for model airplane engines and for certain experimental miniature engines. It is felt that to attain the reliability needed, it will be necessary to keep certain components, such as the breaker points, larger and heavier than might at first seem possible for miniature engines. There can be no compromise on complete reliability of the components of the carburetion and ignition systems, even though there is not the weight reduction here that might be hoped for when going to smaller and smaller engine ratings. A reliable 35 watt engine-generator set will probably have about the same ignition system as that required for a 400 watt set. Some items, like the breaker points, should be the same as those used for large aircraft engines.

The spark plug used should be the maximum size which can be fitted to the engine. The life of the 1/4 inch plugs is too short. A 10 mm plug might be a good compromise for many applications. The coil, condenser, breaker points, and wiring harness must be of proved reliability, even though this will keep the weight of the system greater than might be desired.

Glow ignition is not recommended, unless a special power source is needed for one-shot applications for short periods of operation. The glow plug may fail to start the engine the second or third time it is used. Also, BMEP and BSFC are not as good using glow ignition as with spark ignition. With the electric current turned off, performance with the glow plug is even worse.

4.7 COOLING SYSTEM

While cooling must be provided for both the engine and the generator, the engine heat losses constitute at least 80 per cent of the load on the cooling system. Several types of cooling systems have been studied in some detail to establish their feasibility, but the forced air system using a centrifugal blower is best suited to the requirements. The blower may be located between the engine and generator, pulling air through the generator shaft and forcing air through both the generator and the engine shroud. The former method has the advantage that much of the air could be admitted directly to the blower, by-passing the generator, so that only a fraction of the total air would be pulled through the generator. Thus, the generator temperatures would be kept within allowable limits by using only a fraction of the air required to cool the engine, reducing somewhat the power requirements of the blower.

Studies of the cooling requirements indicate the following general specifications of the cooling system: air flow rate, 15 to 30 cfs; pressure drop across engine, 2 to 20 inches of water; cooling power requirements, 5 to 80 watts.

Reference 4 presents a more detailed discussion of the analysis of the cooling requirements and the merits of several systems. Briefly, it was found that a liquid cooling system could do an excellent job of cooling the engine, but that it made the system unnecessarily bulky and heavy. For these sizes of power plants, it appears that any complication added by liquid cooling would decrease the chances for attaining good reliability of the power plant. Some air cooling for the generator would be required, even if the engine were liquid cooled. Likewise, the system would require either a convective heat exchanger, with some forced air cooling, or a rather large, heavy condenser, in case an evaporative system were used. The only advantages to liquid cooling, then would be a reduced power requirement for the fan or blower and perhaps a small improvement in engine cooling characteristics. Neither of these is worth attaining. These engines seldom detonate, so uniform cylinder temperatures are not required. The cylinder head temperatures can run 400°F without creating problems. In fact, high engine temperatures reduce the deposit problems. Any saving in engine size and weight, obtained by reducing blower power by 75 per cent or so, would be more than lost by the increased weight of any liquid cooling system which could be devised.

Preliminary estimates of a cooling system employing an expendable evaporative fluid show the total weight requirements of the system to be exorbitant for any reasonable lengths of operation of the power plant.

4.8 CONTROLS

The control requirements for miniature engine-generator sets are similar to those for other types of power supplies. The frequency for ac generators, or the voltage for d.c., must be controlled largely by the speed of the prime mover. Other characteristics of the electrical output may be controlled by design of the generator and the electrical auxiliaries. This aspect of control is discussed in Section 4.3 on Generators and in Reference 3, since it deals primarily with electrical generation. The aspect dealing with engine speed control is the principal topic of this section

Several experimental studies were made to determine if the miniature engines were similar to larger engines in regard to variations of speed and power output with changes in certain operating variables. It was found that the miniature, high-speed engines could be controlled best by varying the inlet mixture pressure with a throttle valve, just as is experienced with larger spark-ignition engines. The response to changes in the throttle valve setting, however, is not as good with the miniature engines as it is with the larger engines of the automotive size. The miniature engines are subject to rather wide fluctuations in speed with minor changes in the throttle valve setting. At less than one-half engine load, the throttle gives very poor control of the speed in both two-cycle and four-cycle designs. Other operating parameters, such as exhaust back pressure, spark advance, crankcase compression ratio, or carburetor setting give even poorer control of the speed, as might be expected.

It appears that the speed of a miniature reciprocating engine cannot be controlled within the close limits commonly required for the frequency variations of a.c. power supplies. Some improvement in speed control could be afforded by using a dummy electrical load in the power supply set. Thus, if the external electrical load would suddenly drop from rated to one-third of rated load, the dummy load would automatically cut in so that the generator and engine outputs would be changed only slightly by the change in the external load. This sounds inefficient, but the total energy dissipated through the dummy load would be rather small. Also, the engine has nearly the same fuel consumption at part load as it does at rated load. Thus, a combination of throttle control on the engine plus the use of the dummy load on the over-all power source might provide an adequate control of the a.c. frequency or of the d.c. voltage.

4.9 STARTING SYSTEMS

Two types of starting systems must be considered, manual and automatic. The manual system assumes the presence of a human being to crank the engine over and possibly also to make certain adjustments after the engine is running. The automatic system requires no person present to start and operate.

The following types of manual starting systems appear feasible, considering the physical limitations of the human being:

(1) manual rope-pull starter
(2) hand-cranked inertia starter
(3) hydraulic cranking motor

Of these three, the manual rope-pull starter is the system requiring the least weight and volume, and is used extensively for many commercial applications for engines up to 50 hp. However, higher cranking speeds and torques may require the use of either of the last two methods. The hand-cranked inertia starter employs a flywheel as a means of energy storage subsequently to crank the engine. The hydraulic cranking motor uses the compression of a liquid-gaseous system to store energy for the high demand during engine cranking.

Five types of automatic starting systems have been found to be feasible for miniature engine-generator sets:

(1) cartridge starter
(2) electrical cranking motor
(3) electrically cranked inertia starter
(4) compressed gas starter
(5) spring starting system

The cartridge starter employs the burning of a cartridge composed of a material such as mechanite to generate a high gas pressure which is used to crank the engine over. Methods (2) and (3) use an electric motor to crank the engine over. The first of these employs a motor with sufficient torque to crank the engine over directly. Electric current is supplied from batteries. The second of these uses a smaller motor to accelerate a high-speed flywheel prior to engaging the engine.

A compressed gas system employing high pressure nitrogen to drive a vane type starting motor was used for the Ruckstell-Hayward Power Source for Radio Beacon AN/ART-27(XA-1). This system appears to have potentialities, but was never fully developed. In addition to its regular operating fuel, this system was to use hydrogen for early engine warmup; however, it was found that the engine did not operate satisfactorily with this fuel. Except for defective pressure regulators, the nitrogen vane motor cranking system seemed to be quite satisfactory.

The spring starting system, using a clock-type, spiral-wound spring which is wound about the engine crankshaft, would be compact and extremely reliable.

All of the starting systems described briefly above are discussed in greater detail in WADC TR 53-180, "Study of Miniature Engine-Generator Sets, Part IV."

4.10 NOISE REDUCTION AND RADIO SUPPRESSION

In these areas work only of an exploratory nature was conducted by this project, since greater effort was devoted to studying methods of achieving performance and reliability. It was found that these high-speed engines have an unusually intense sound level caused by the ring of the metallic parts. The exhaust noise and induction noise can be dampened to a fairly reasonable level, but the high-frequency ring of the metal components appears to be essentially irreducible. An exhaust muffler and an induction system silencer almost double the size of the engine and generator, if they are to be effective. These components do not increase the weight of the set a great deal, of course, but the over-all size is appreciably increased. Without muffler and inlet silencer, the sound level of a miniature engine-generator set is comparable to that of a model airplane engine--audible at 800 yards and definitely annoying at 10 feet.

Limited test work with a commercial muffler are reported in Reference 4. No test work was attempted toward the reduction of the noise caused by the metallic parts.

No work was performed to reduce radio interference with this equipment, but the same problems exist for it as for larger equipment. The techniques in current use for suppressing radio interference from military engine-generator sets would be required, Reference 11. These would consist of using integrally shielded resistor-type spark plugs; completely enclosing the distributor, coil, magneto, and voltage regulator in an aluminum or steel housing; and enclosing all exposed wiring in three-layer flexible metallic hose, with end connectors soldered to the hose. In addition, the generator would require capacitors to bypass the commutator or slip-ring brushes to the inside of the generator housing, capacitors to bypass the generator output terminals to the housing, and shielded leads from the output terminals to the power-line filter, if any. The generator frame, brush rig, and bell housing must be bonded electrically to each other and to the assembly frame with tooth-type lock washers. The same is true for the magneto and for the metal housings enclosing the components of the ignition system.

It is evident that all of these provisions will add materially to the over-all equipment weight and size; yet they have been shown to be essential for practically all military applications of power sources. This is one more reason why practical engine-generator sets of miniature size cannot attain the very low values of weight per unit of rated output which was hoped for at the beginning of the contract.

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